



Concluding Remarks: Dark Matter

Eric Charles (SLAC National Accelerator Lab.)

2nd World Summit on Exploring the Dark Side of the Universe
26 June 2017,
Pointe-à-Pitre, Guadeloupe



Outline

- Introduction
 - Theme: communication between communities
- A high level tour of science topics with various personal biases and a few random asides



Theme: Communicating between Communities

- This conference brings together people for multiple communities:
 - Accelerator-based dark matter detection
 - Direct dark matter detection
 - High-Energy Astronomy / Astrophysics
 - Cosmology
 - Neutrinos
 - Particle Theory / phenomenology
 - Black holes & gravitation
- We all had to take a step back and focus on things that will be of interest to people outside our specific communities
 - I hope this talk follows in that spirit, i.e., I'm not going to be saying a lot about nano-Bq / kg, pseudo-rapidity cuts, or γ -ray telescope instrument response functions



Topics Covered

- Dark matter theory
- Searches
 - Accelerator Based Searches
 - Direct detection
 - Indirect detection
- Cosmology & Astrophysical Dark Matter



THEORY

What do we know about dark matter

What do we know about DM?

Makes up 23% of the universe

Has attractive gravitational interactions (like ordinary matter but is non-baryonic)

Is either stable or has a lifetime $\gg t_U$.

Is not observed to interact with light (weakly coupled, neutral or "milli-charged").

The bulk of the DM must be dissipationless, but part of it could be dissipative

Has been mostly assumed to be collisionless, however the upper limit on DM self-interactions is very large.

Was non-relativistic at time of CMB (Cold or Warm possible, to account for all the large scale structure observations, hence New physics BSM needed)



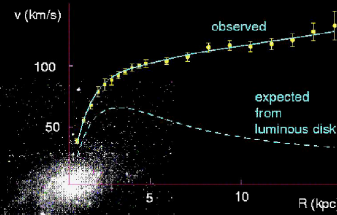
What is it?
Which are its det.
Does it have Higgs
How to search for

Carena

Evidence for Dark Matter

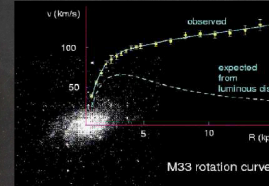
The rotation of the stars around the center of the galaxies is not consistent with the amount of mass observed $(L/M \text{ ratio})_{\text{SUN}}$

Spherical dark matter halo



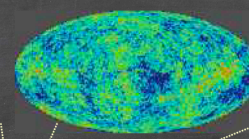
M33 rotation curve

Galactic rotation curves

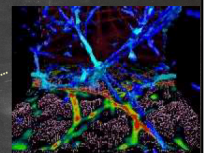


Because the existence of DM is the strongest evidence for BSM!

CMB: WMAP and PLANCK



Large Scale Structures



Bullet cluster



Gravitational lensing



collider interplay in decoding the nature of DM

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Martinez

WSEDS Workshop, M.

Considered the ultimate demonstration of the presence of Dark Matter since this does not involve Newton's Law

There is overwhelming evidence that 1) dark matter exists, and 2) it is not made of baryons.

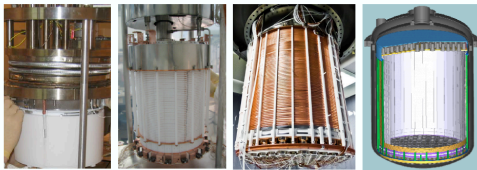
Beyond that, we don't know much about the particle nature of dark matter

Direct, Indirect, Accelerator-based DM Searches

Direct Detection

The XENON legacy

XENON10 2005-2007 XENON100 2008-2016 XENON1T 2012-2018 XENONnT 2019-2023

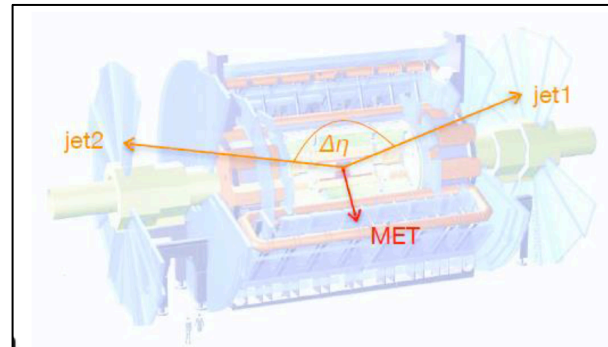


25 kg	161 kg	3.2 ton	8 ton
15cm drift	30 cm drift	1 m drift	1.5 m drift
$\sim 10^{-43} \text{ cm}^2$	$\sim 10^{-46} \text{ cm}^2$	$\sim 10^{-47} \text{ cm}^2$	$\sim 10^{-48} \text{ cm}^2$
BG $\sim 1000 \text{ (keV t yr)}^{-1}$	BG $\sim 5 \text{ (keV t yr)}^{-1}$	BG $\sim 0.2 \text{ (keV t yr)}^{-1}$	BG $\sim 0.02 \text{ (keV t yr)}^{-1}$

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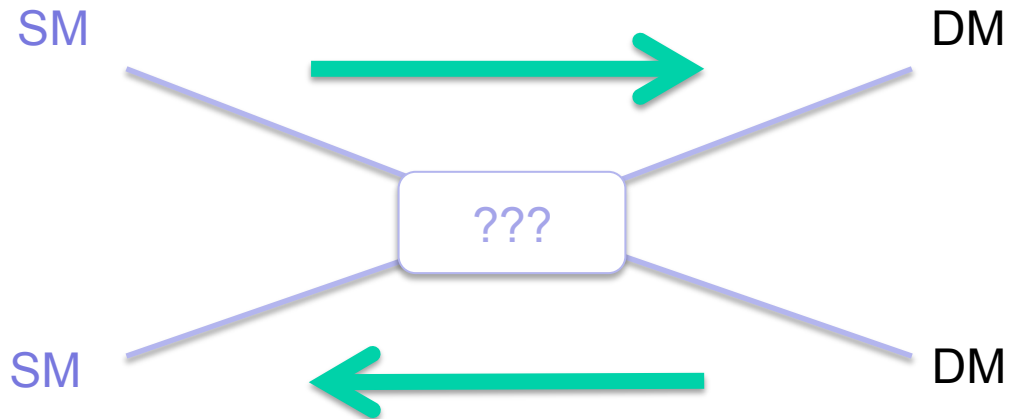
Belayaev, D'Angelo, Messina
Gerber, Kouvaris, Chevalier

Key point: if you have a theory of the particle interactions you can predict the rates for all of these processes, **and translate results between communities.**

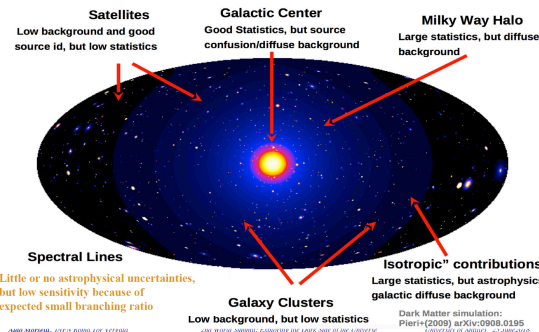


Martinez, Gomez-Ceballos,
Dorigo, Royon, Wei, Kitali,
Williams

Collider Searches



Dark Matter Search: Targets and Strategies

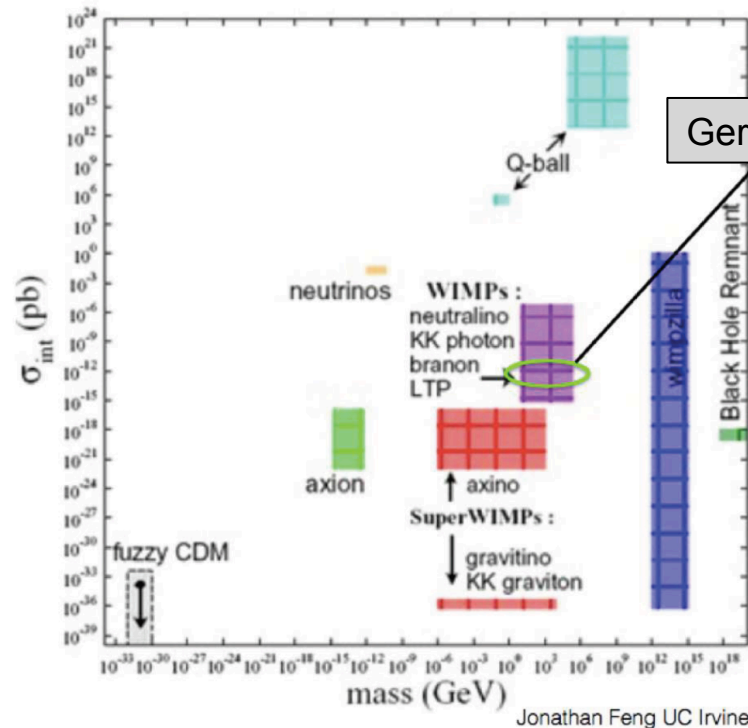


Morselli, Vincent,
Humensky, Charles,
Gomez-Vargas, Aguilar

Indirect detection

Dark Matter Parameter space: lamppost physics

Dark Matter Parameter Space



K Palladino

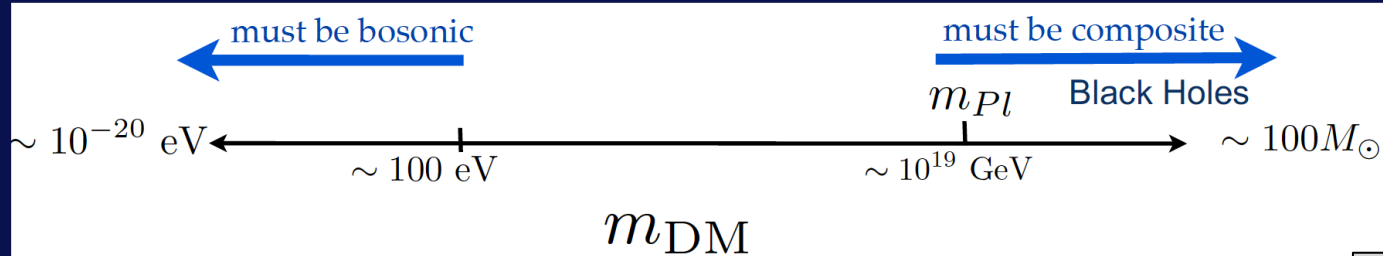
This figure showed up in several talks. Interestingly, it was typically followed by an explanation of why the speaker was going to focus on WIMPs (or in a few cases, axions or primordial black holes).

Kouvaris, Chevalier, Williams

Garcia-Bellido, Vidotto

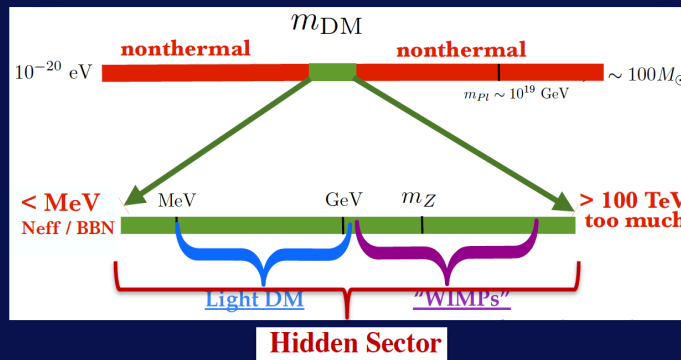
What types of theories are we looking at?

Particle physics properties constraints the range of possible masses

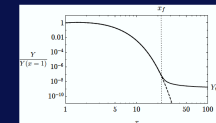


Carena

Thermal Equilibrium:
Narrows viable Mass range



The WIMP Miracle



Taking $x_F \sim 10$ and $\langle \sigma v \rangle \sim \alpha^2/m^2$, the fraction of critical density contributed by the DM today is

$$\Omega_{\chi^2} \sim (10^{-26} \text{ cm}^3/\text{s}) / \langle \sigma v \rangle \approx 0.1 (0.01/\alpha)^2 (m/100 \text{ GeV})^2$$

→ correct abundance today as measured by Planck and WMAP, for $\alpha \sim 0.01$ and $m \sim 100 \text{ GeV}$

the "WIMP miracle"

Weak-scale DM naturally gives the correct DM density
Many well-motivated BSM models contain a parity symmetry
SM \rightarrow SM BSM \rightarrow - BSM

e.g. R-parity in SUSY (proton decay)
T-parity in little Higgs models (precision EW observables)
KK-parity in extra-dimensional models

Lightest Parity Odd Particle is stable, may be a DM candidate

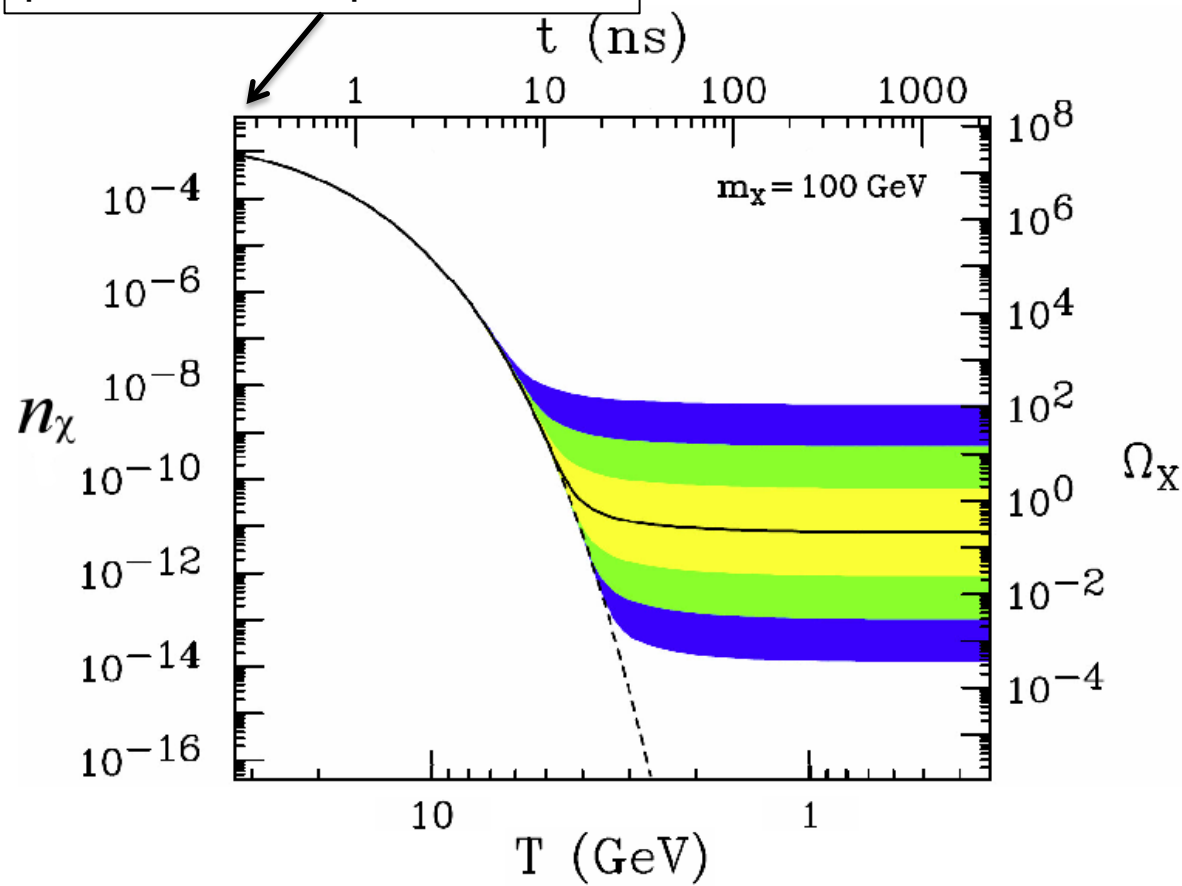
Always produced in pairs and leaves detector as MET

A wide-ranging of experimental programs targeted for WIMP searches

"Good news: Most discoverable DM candidates are in Thermal equilibrium with us in the early universe" – Marcela Carena

Aside: Dark Matter as a Thermal Relic

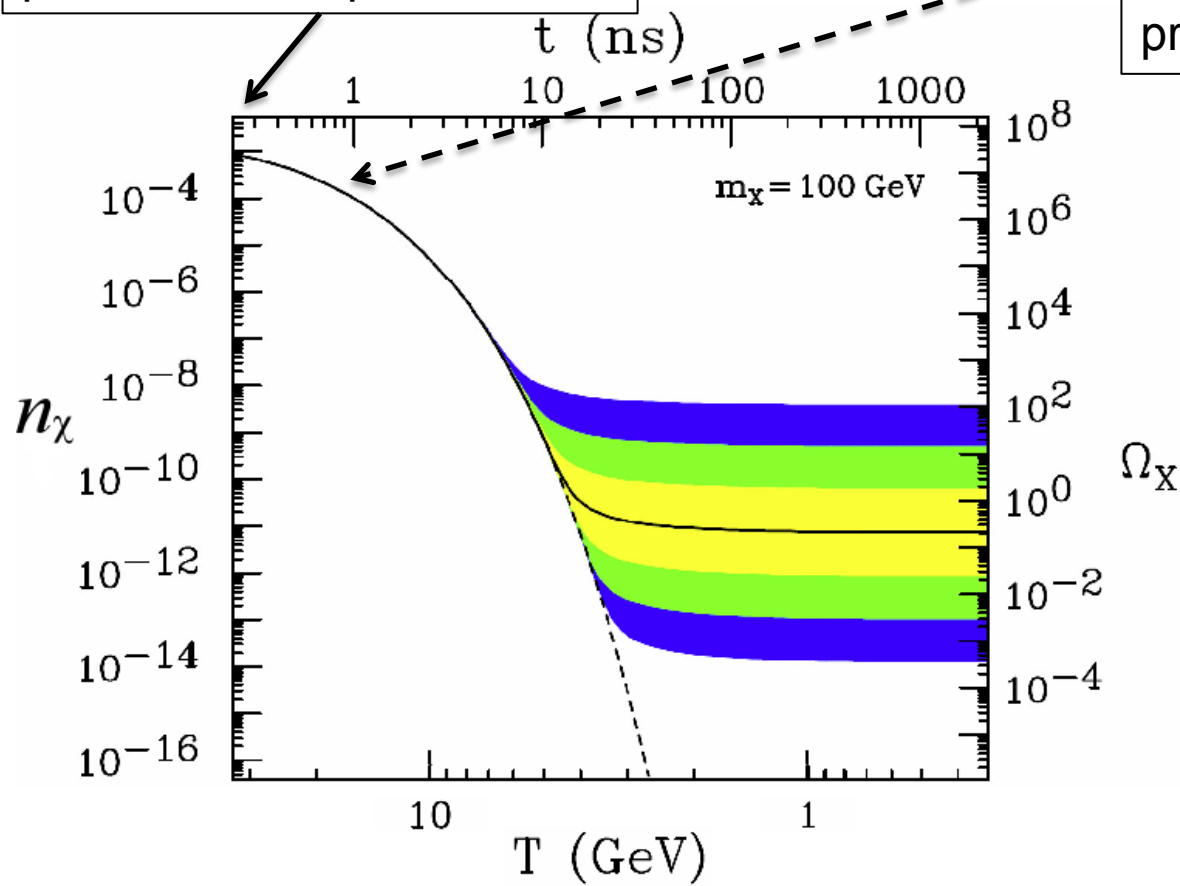
1. For the first 0.1 ns of the Universe it is hot enough to produce exotic particles.



Aside: Dark Matter as a Thermal Relic

1. For the first 0.1 ns of the Universe it is hot enough to produce exotic particles

2. After about 0.1 ns, the Universe has cooled enough that exotic particles are no longer produced, but can annihilate.

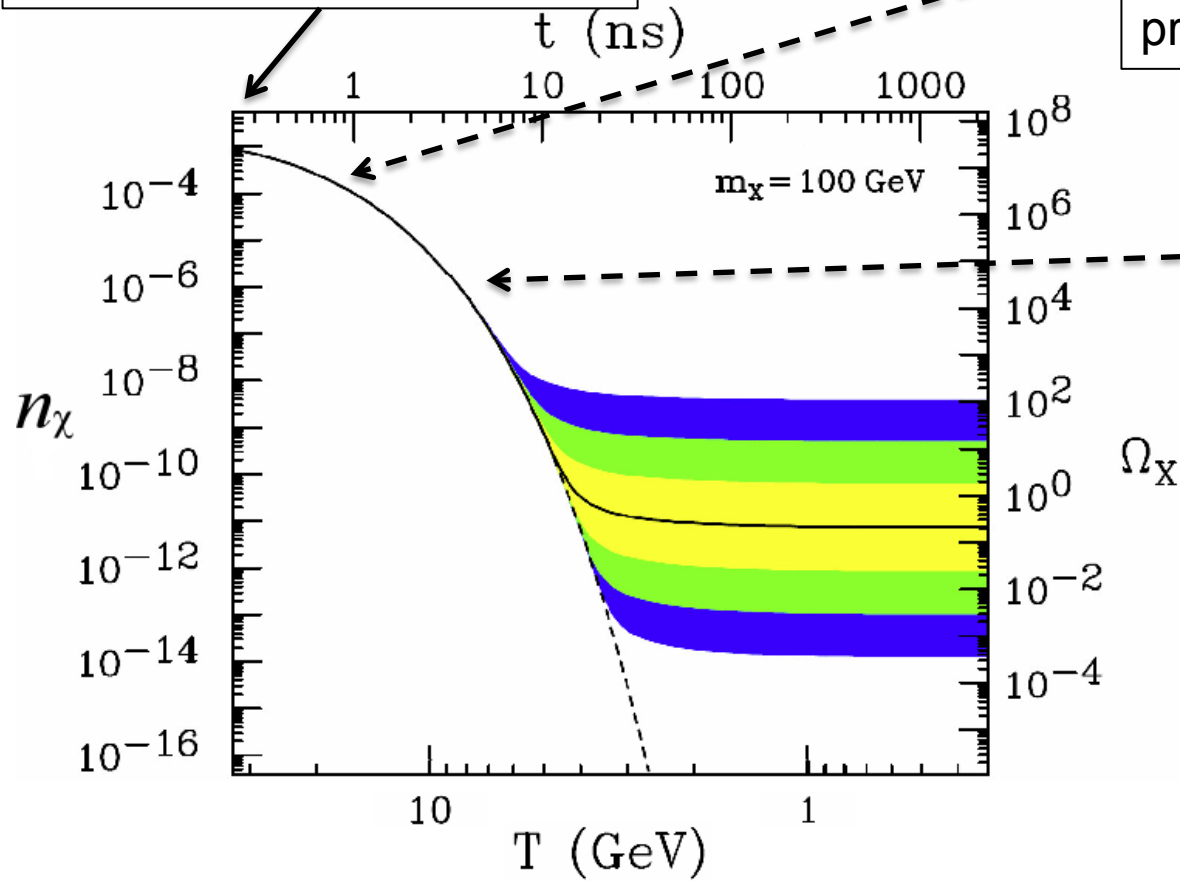


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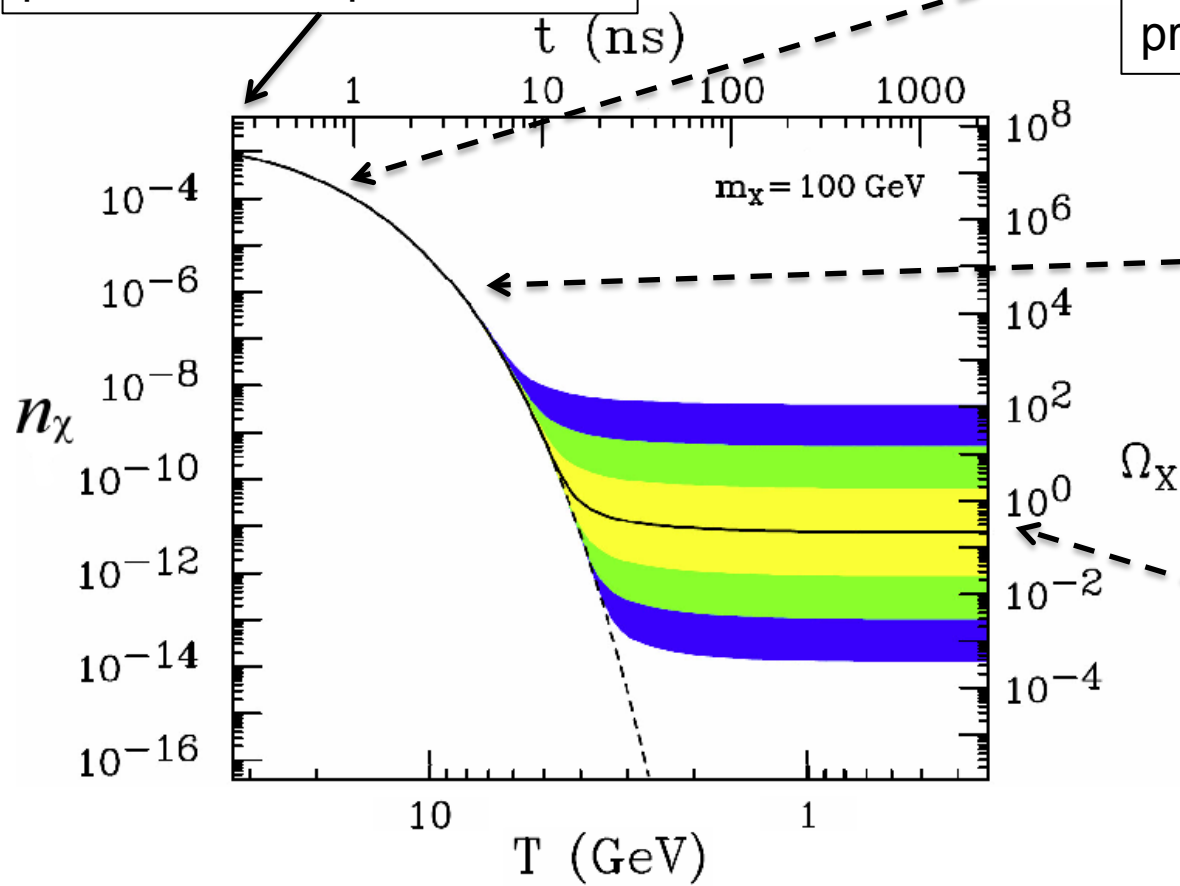
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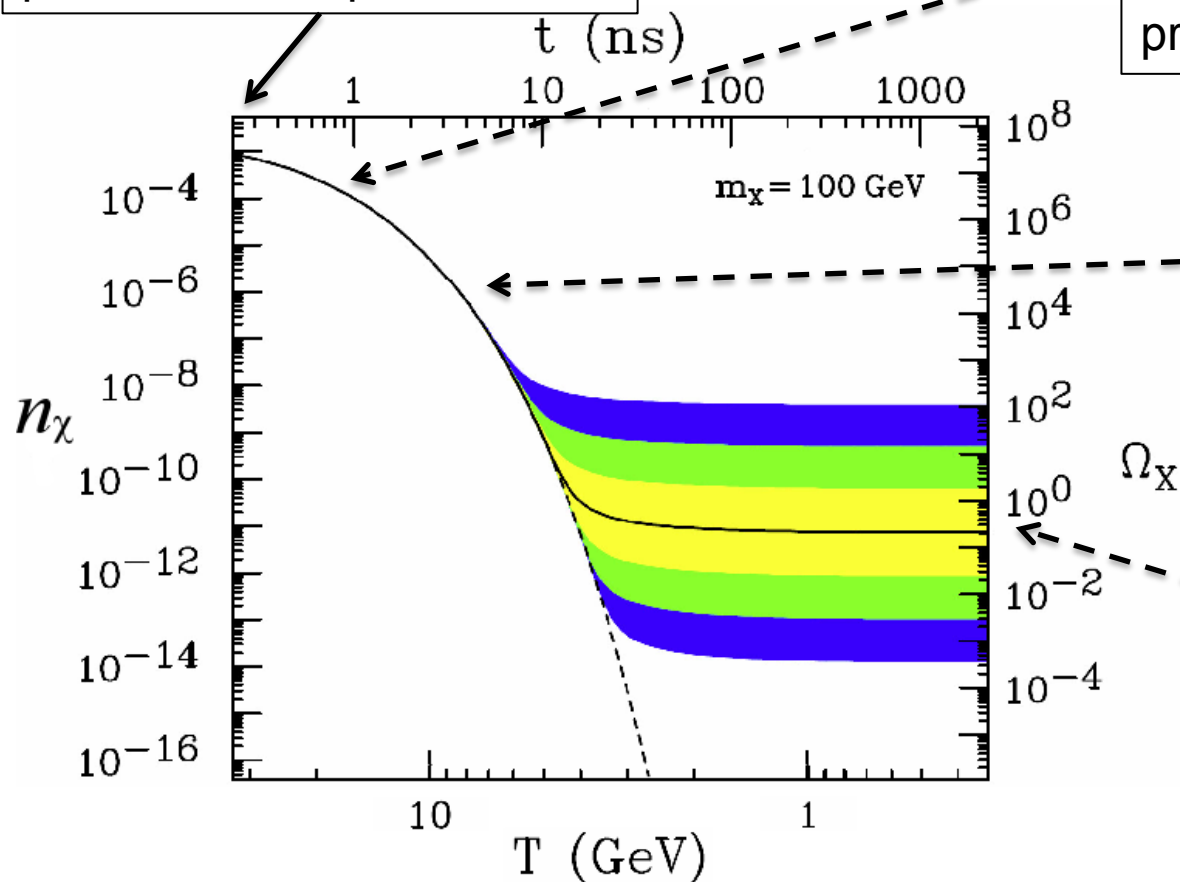
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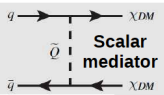
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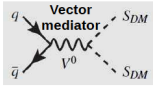
5. The surviving fraction depends critically on the annihilation cross section (i.e., probability): small differences would yield very different dark matter densities today.

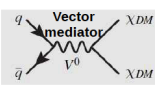
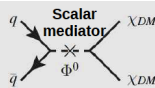
DM Theory Space is Vast and Diverse

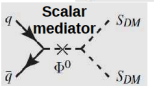
Mapping EFT operators to simplified models

C5, C5A $\frac{1}{\Lambda^2} \phi^* \phi G^{\mu\nu} G_{\mu\nu} \rightarrow \frac{1}{\Lambda^2} \phi^* \phi \tilde{G}^{\mu\nu} G_{\mu\nu} \rightarrow$ 


D1T-D4T $\frac{1}{\Lambda^2} \bar{\chi} q \bar{q} \chi \rightarrow$ 

C3 $\frac{i}{\Lambda^2} [\phi^* (\partial_\mu \phi - (\partial_\mu \phi^*)) \phi] \bar{q} \gamma^\mu q \rightarrow$ 

D1-D4, D5-D8 $\frac{1}{\Lambda^2} \bar{\chi} \gamma^\mu \chi \bar{q} \gamma_\mu q \rightarrow \frac{1}{\Lambda^2} \bar{\chi} \chi \bar{q} q \rightarrow$  

C1 $\frac{1}{\Lambda^2} \phi^* \phi \bar{q} q \Phi \Rightarrow \frac{v}{\Lambda^2} \phi^* \phi \bar{q} q \rightarrow$ 

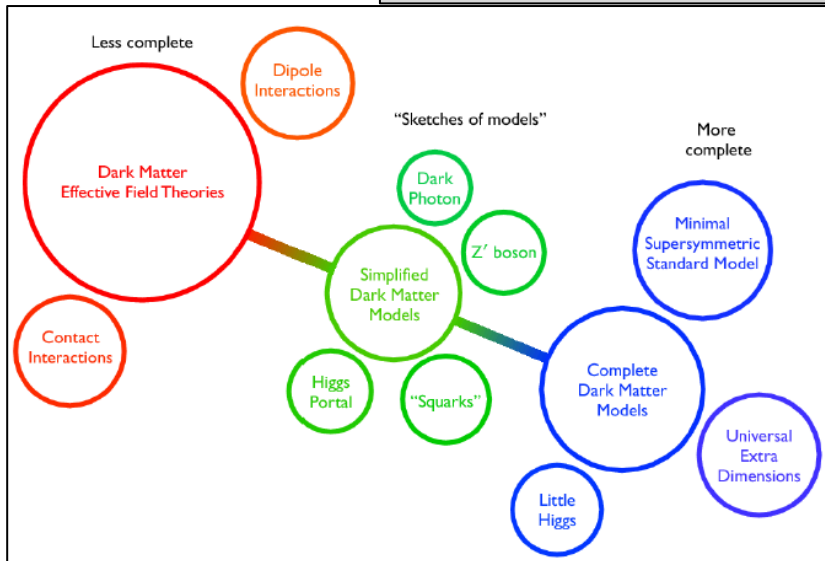
D9, D10 $\frac{1}{\Lambda^2} \bar{\chi} \sigma^{\mu\nu} \chi \bar{q} \sigma_{\mu\nu} q \rightarrow \frac{8}{\Lambda^2} [\bar{\chi} q \bar{q} \chi - \frac{1}{4} (\bar{\chi} \chi \bar{q} q + \bar{\chi} \gamma^5 \chi \bar{q} \gamma^5 q + \bar{\chi} \gamma^\mu \chi \bar{q} \gamma_\mu q - \bar{\chi} \gamma^\mu \gamma^5 \chi \bar{q} \gamma_\mu \gamma^5 q)]$

Alexander Belyaev  DD and collider interplay in decoding the nature of DM

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Belyaev

Belyaev, Carena, LHC talks



Key point: theory space is huge, some amount of simplification & organization is needed to approach the problem in a sensible fashion

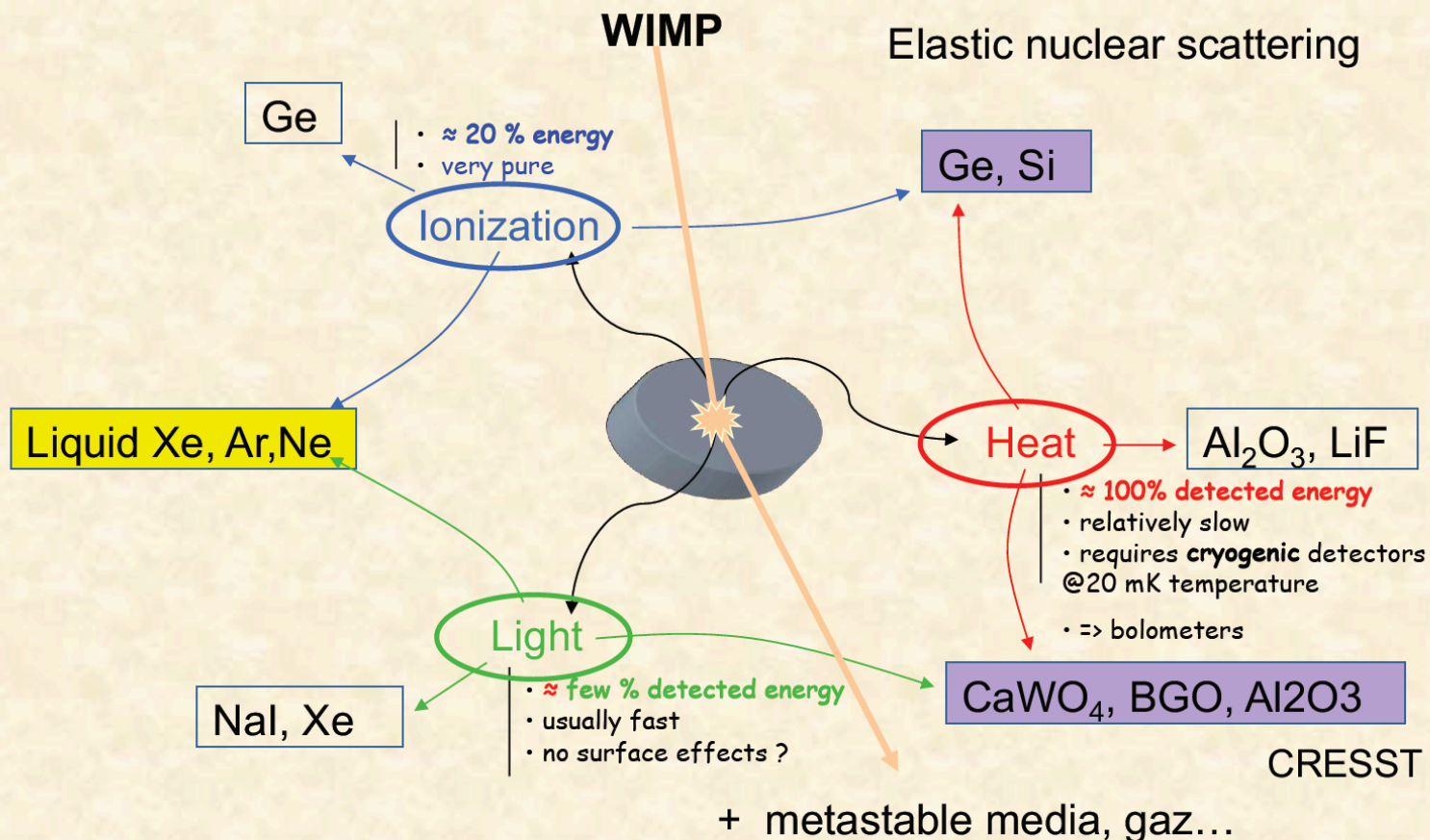


DIRECT DETECTION

Direct Detection Techniques

Gebier, Belayaev

Direct detection techniques



DM Scattering Produces Heat, Light & Ions

Masbou, EDU 2017
Recontres de Viet Nam

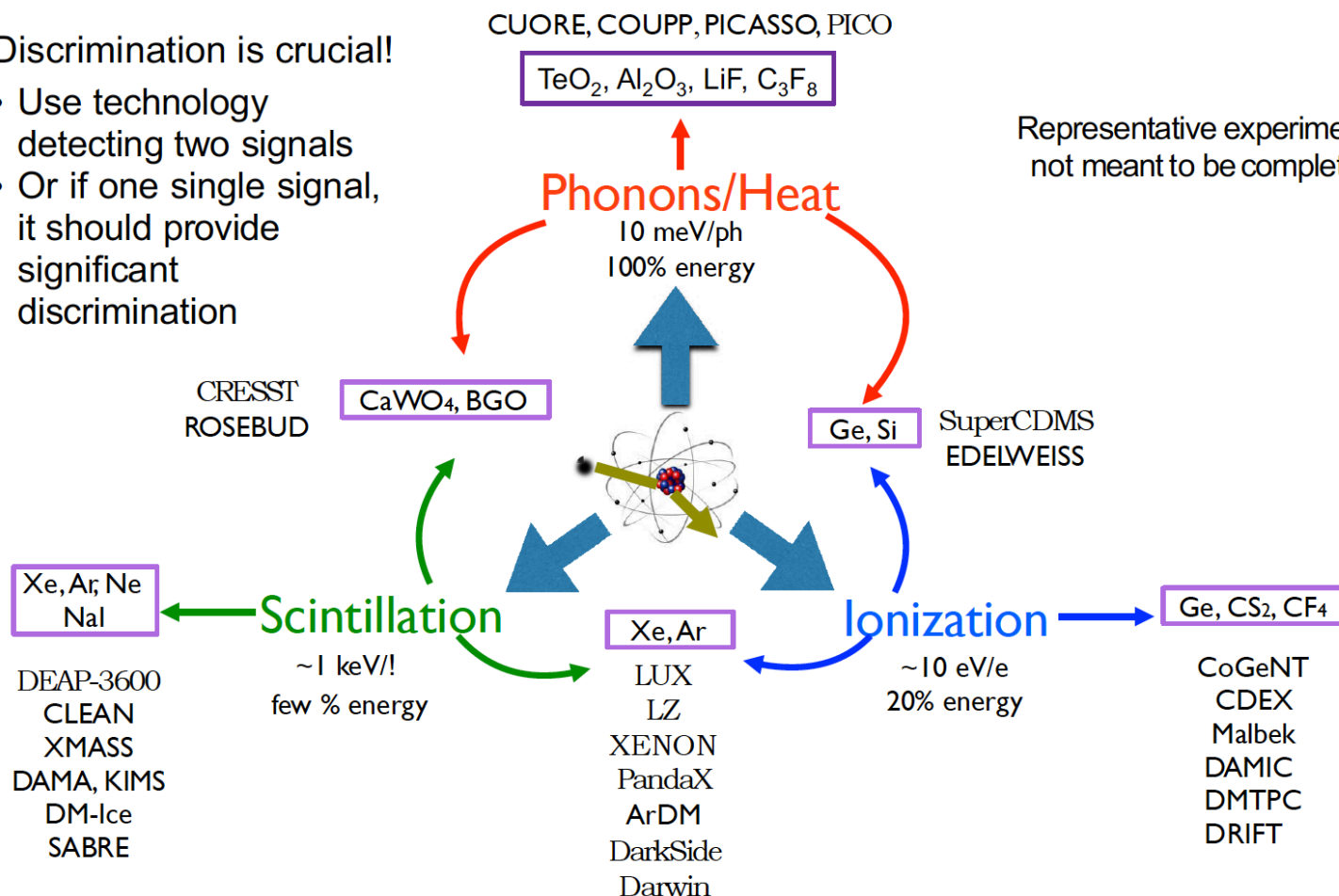
Direct Detection Techniques

from Carmen Carmona

Discrimination is crucial!

- Use technology detecting two signals
- Or if one single signal, it should provide significant discrimination

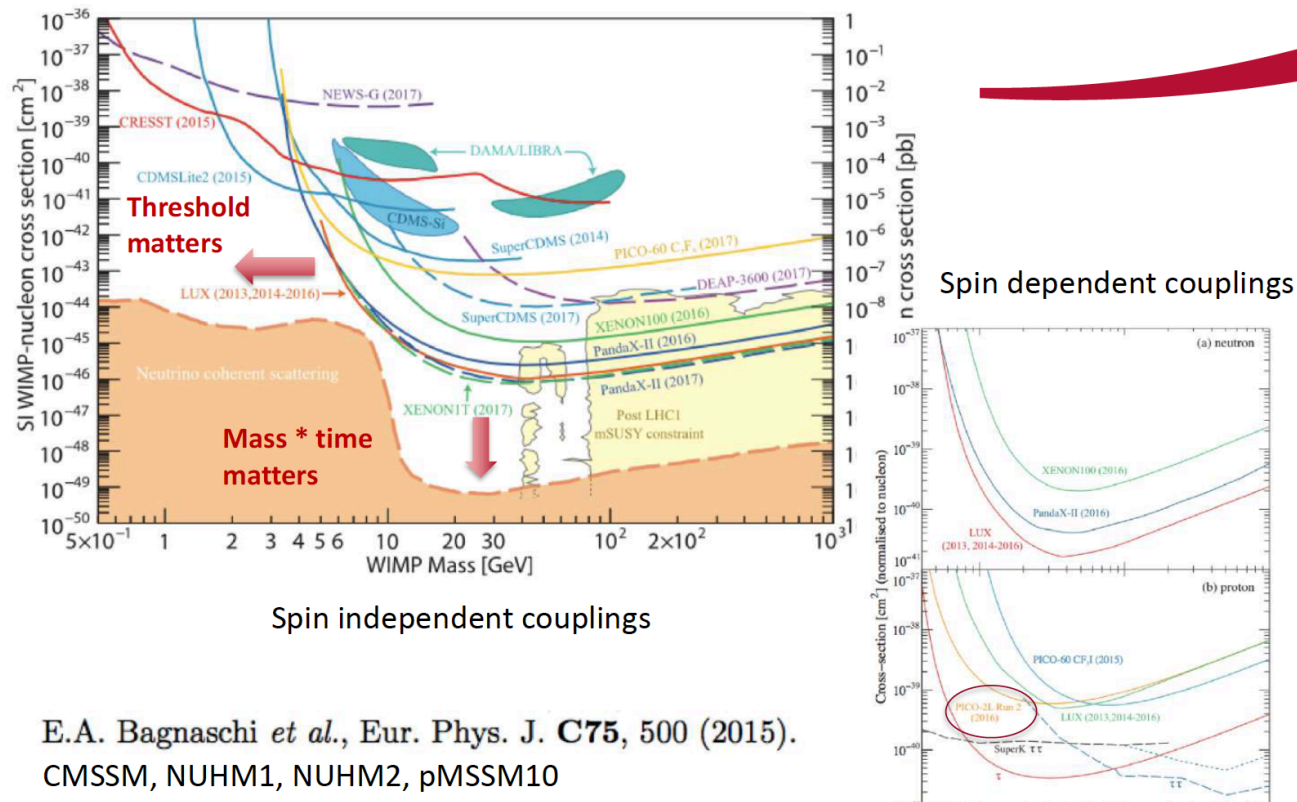
Representative experiments,
not meant to be completed



One slide summary of Direct Detection Status

Now : actual results (RPP/PDG, Dark Matter review 2018)

Gebier

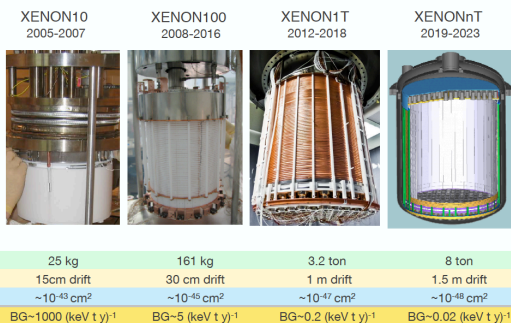


Direct detection of WIMPs: > 10 GeV focus is on making larger volumes with low backgrounds, $< \text{few GeV}$ focus is on lowering effective threshold

Also, cottage industry in understanding the DAMA/Libra results

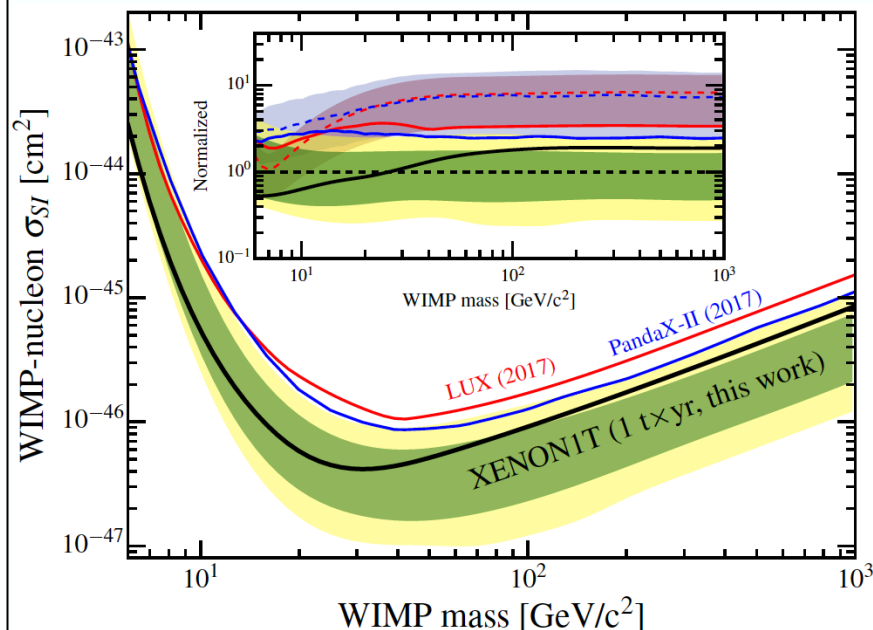
High-mass DM, Xenon 1T Results

The XENON legacy



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1T Dark Matter Search

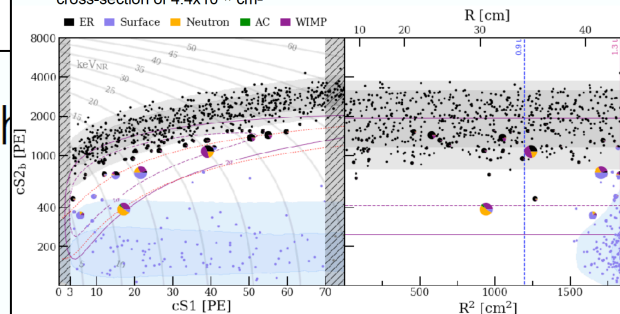


Minimum at $4.1 \times 10^{-47} \text{ cm}^2$ for a WIMP of $30 \text{ GeV}/c^2$

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Dark Matter Search Results

- Results interpreted with un-binned profile likelihood analysis in cs_1 , cs_2 , R , z space
- piechart indicate the relative PDF from the best fit of $200 \text{ GeV}/c^2$ WIMPs with a cross-section of $4.4 \times 10^{-47} \text{ cm}^2$



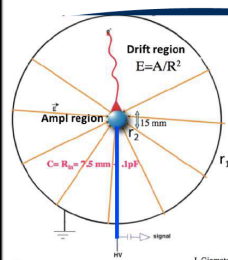
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- Most stringent 90% CL upper limit on WIMP-nucleon cross section above 6 GeV
- Factor of 7 more sensitivity compared to previous experiments
- ~ 1 sigma upper fluctuation from median sensitivity

Messina

Low mass WIMPs, pushing down the threshold, reducing background

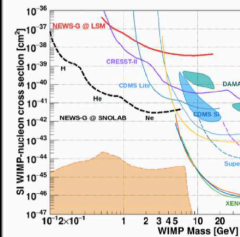
Spherical gas detectors New Experiments With Spheres - Gas



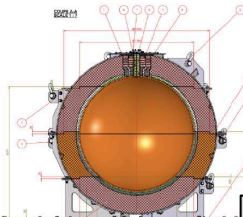
Low mass



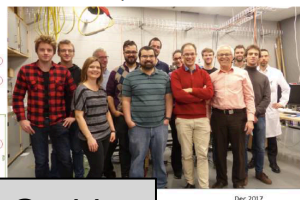
- Sphere cavity + spherical sensor + HT
- => Low threshold (low C), does not depend on size
- Track/point like identification
- Fiducial volume selection by risetime
- Flexible (P, gaz)
- Large mass / large volume (30 kg) with single channel
- 1 low activity 60 cm Ø in operation @ LSM
- Project of 140 cm at SNOLAB



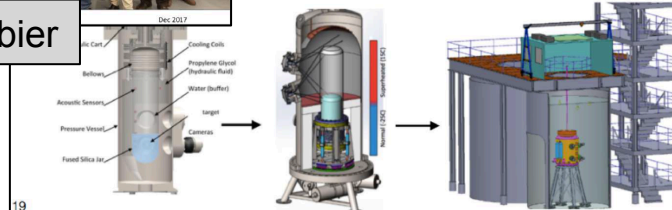
In SNOLAB mid 2019



10 labs Europe NA, Queen's team here



Gerbier



Kouvaris

DAMASCUS: Dark Matter on Supercomputers

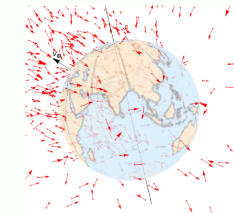
Performing a simulation of trillions of DM particles on ABACUS

- fully parallelized code
- publicly available
- state-of-the-art composition and density profiles of the Earth
- Precise Recoil Spectrum

Test self-consistency of experiments



clusive Dark Matter



Spin dependent

- Additional PICO 60 analyses forthcoming
- PICO 40L coming online this summer (2018) with C_3F_8 target and inverted vessel
- PICO 500 scheduled to begin construction in 2019

Many developments in searching for low mass WIMPs:

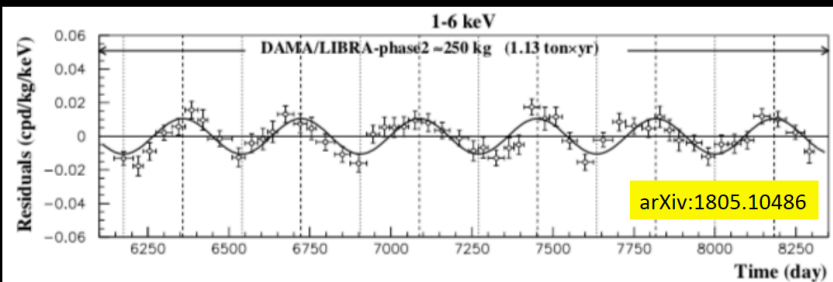
New target materials

Using modulation signals to reduce noise

Directional direction

Reproducing the DAMA / LIBRA results

...and now including DAMA/LIBRA-Phase2



- 20 annual cycles (DAMA/NaI + DAMA/LIBRA-Phase1 + DAMA/LIBRA-Phase2)
- Exposure: 2.46 ton x yr
- $\chi^2/\text{ndf} = 150/52$ (Ph2-only 1-6keV); 199/102 (Ph1+Ph2 2-6keV)
- 12.9σ significance
- (0.999 ± 0.001) year period
- Phase is (145 ± 5) days vs. Exp. DM phase 152.5 days
- Amplitude: (0.0103 ± 0.0008) cdp/kg/keV, i.e. $\sim 1\%$ of the experimental rate.

EDSU 2018

D. D'Angelo - DM Modulation

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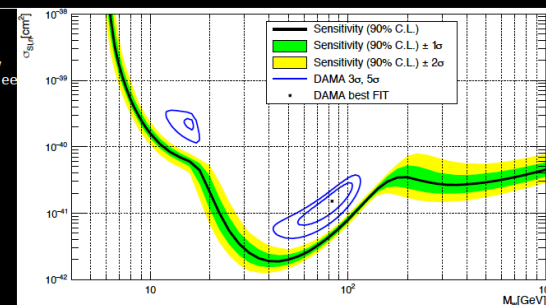
d'Angelo

SABRE Sensitivity

arXiv:1806.09340

1. Model-independent approach: 50k toy-MC data sets with/without signal yield $6\sigma/5\sigma$ power to verify/refute the claim at 90% C.L.
2. Classic sensitivity curve to SI WIMP-nucleon interaction

Exposure: 50 kg x 3 yr
 Background: 0.22 cpd/kg/keV
 Quenching: Xu et al. PR C92 (2015) 015807.
 Systematics: quenching, resolution, efficiency, background
 DAMA islands: Phase1 only



EDSU 2018

D. D'Angelo - DM Modulation

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Several experiments coming online to attempt to reproduce DAMA / Libra result as closely as possible. Approaching required sensitivity.

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Chevalier

[illegible]

Future experiments: Quax

Future experiments: Quax

Future experiments: Orpheus

- Open Fabry-Perot resonator and a series of current-carrying wire planes
- Searches for axion like particles in the 68.2-76.5 μeV mass range
- Potentially searches in the mass range 40-400 μeV in the future
- $g_{\text{avy}} \sim 1\text{e-14}$

Future experiments:
MadMax

Future experiments:
MadMax

Future experiments: Shuket
(Search for extra-U(1) dark matter with a spherical Telescope)

- dish antenna
- no B field \rightarrow hidden photon

Radius of curvature of the dish

Magnetized metallic dish

GHz waves

Antenna

Low-noise amplifiers

Shielding

Spectrum analyzer

B

Waveguide coupling

23

Key point: ultra low-mass DM is bosonic, and acts more as a field than as particle. Look for SM particle coupling to field.



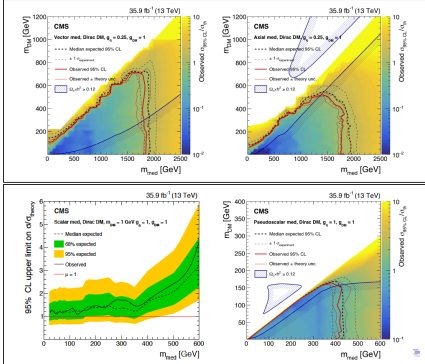
ACCELERATOR SEARCHES

Searches for DM Candidates at the LHC

Gomez-Ceballos

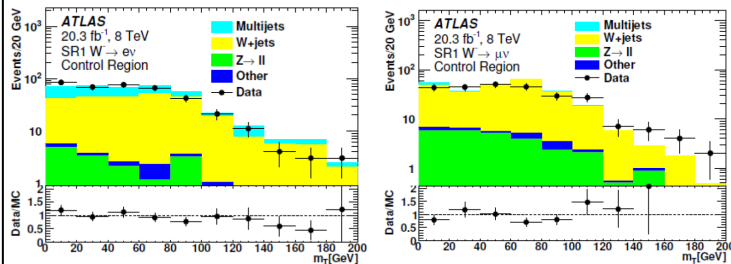
Mono-jet/Mono-V (qq) Analysis: 95% CL Limits

Limits for different mediator types and for different coupling strengths



Control and validation regions

- W+jets estimated using $W \rightarrow e\nu/\mu\nu$ control regions
- $W_{SR} \sim (W_{SR}/W_{CR})^{MC} \times W_{CR}$
- Fits to E_T^{miss} and transverse mass: $m_T = \sqrt{2p_T^L E_T^{miss} [1 - \cos(\Delta\phi_{L, E_T^{miss}})]}$



Dorigo

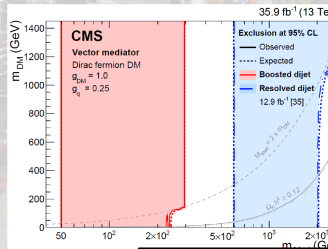
DM Results of Boosted Dijet Search

Results of search can be cast in context of simplified DM model.

95% CL limits are reported in $M_{DM}:M_{med}$ plane (dashed=exp limits)
Branching fraction of 100% is assumed for a leptophobic vector mediator decaying to dijet.
The exclusion is computed for a quark coupling choice $g_q = 0.25$ and $g_{DM} = 1$.
Excluded regions also shown from the dijet resolved analysis[1]

Results are compared to constraints from cosmological relic density of DM (light gray) determined as described in [2] from astrophysical measurements [3,4] using MADDM.

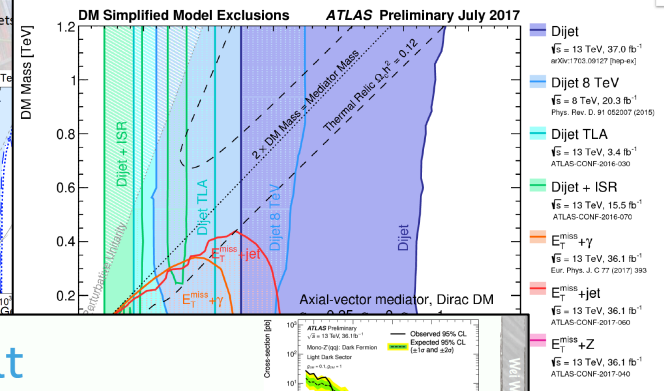
- [1] CMS Coll., Phys. Lett. B 769 (2017) 520
- [2] T. du Pree, K. Hahn, P. Harris, and C. Roskies, arXiv:1603.08525 (2016)
- [3] WMAP Coll., Astrophys. J. Suppl. 170 (2007) 335



Kitali

Martinez

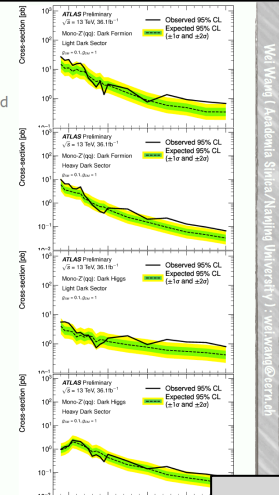
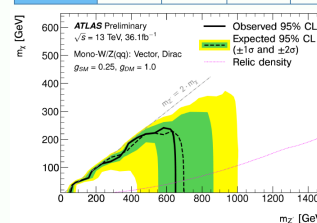
Summary Mono-X + Dijets



Result

- No significant excess over the SM prediction observed
- Set limit on signal strength μ at 95% CLs for each signal model and interpreted them into limit on:
 - DM and mediator mass for mono-V model
 - branching ratio of $H \rightarrow$ invisible decay
 - cross section for mono-Z' model

	observed	expected	+1 σ	-1 σ
limit on $BR(H \rightarrow inv)$	0.83	0.58	0.81	0.42

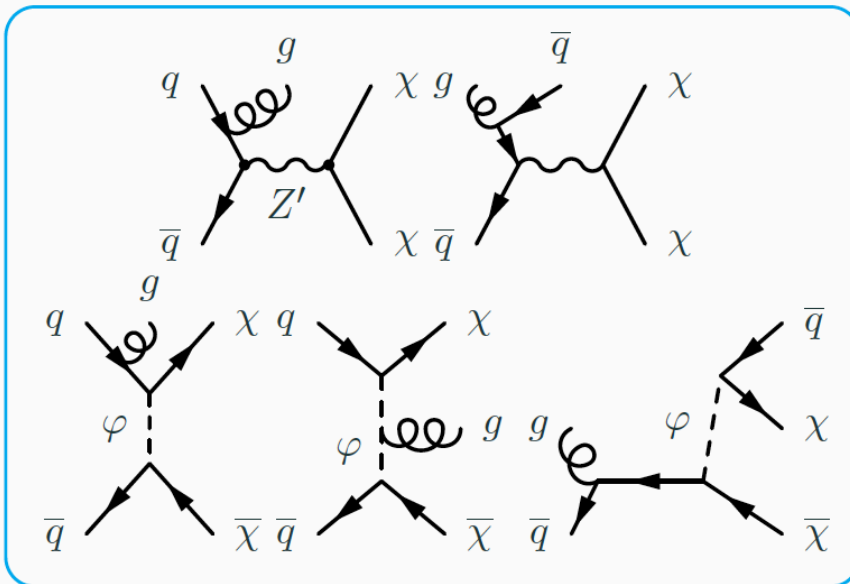


Wang

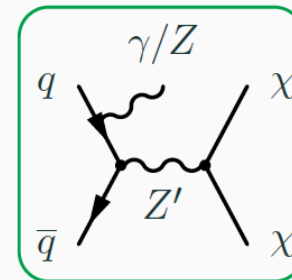
- Several talks about searches for different topological signatures at the LHC
- As an outsider, biggest questions are: how they all tie together, and what are the implications for WIMPs as DM



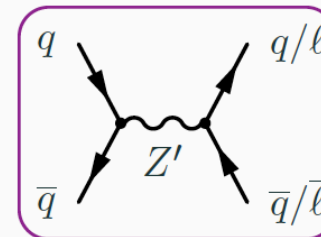
Event topologies



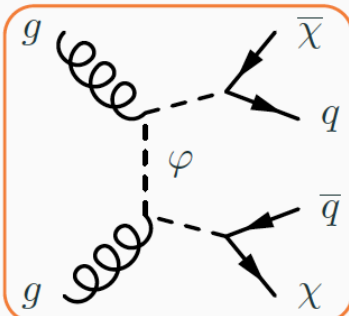
mono-jet



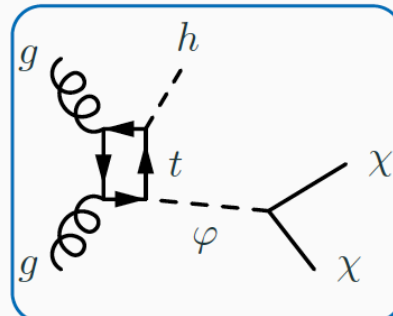
mono- γ/Z



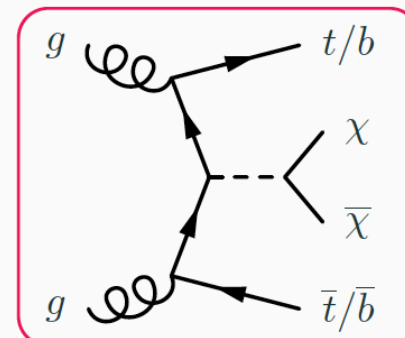
resonant searches:
di-jet, di-leptons...



di-jet + MET



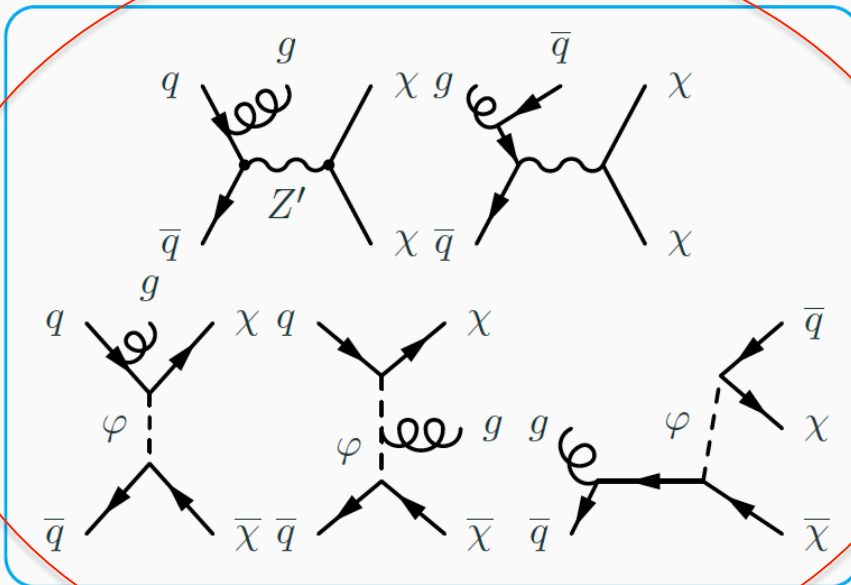
mono-higgs



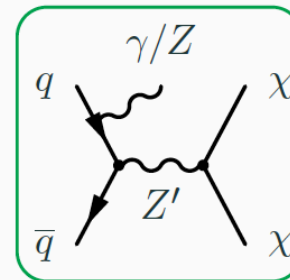
di-top/bottom + MET



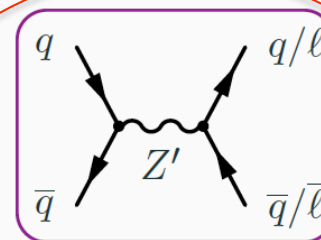
Event topologies



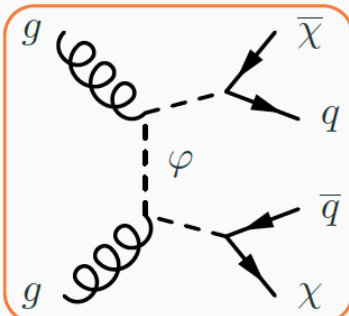
mono-jet



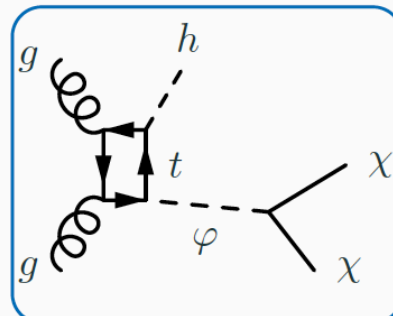
mono- γ/Z



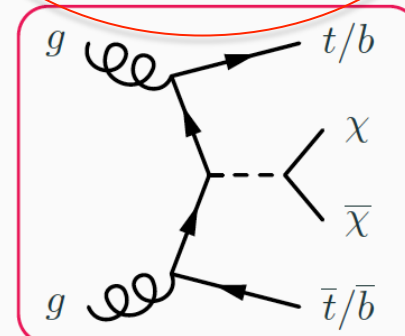
resonant searches:
di-jet, di-leptons...



di-jet + MET



mono-higgs



di-top/bottom + MET

Event Topologies

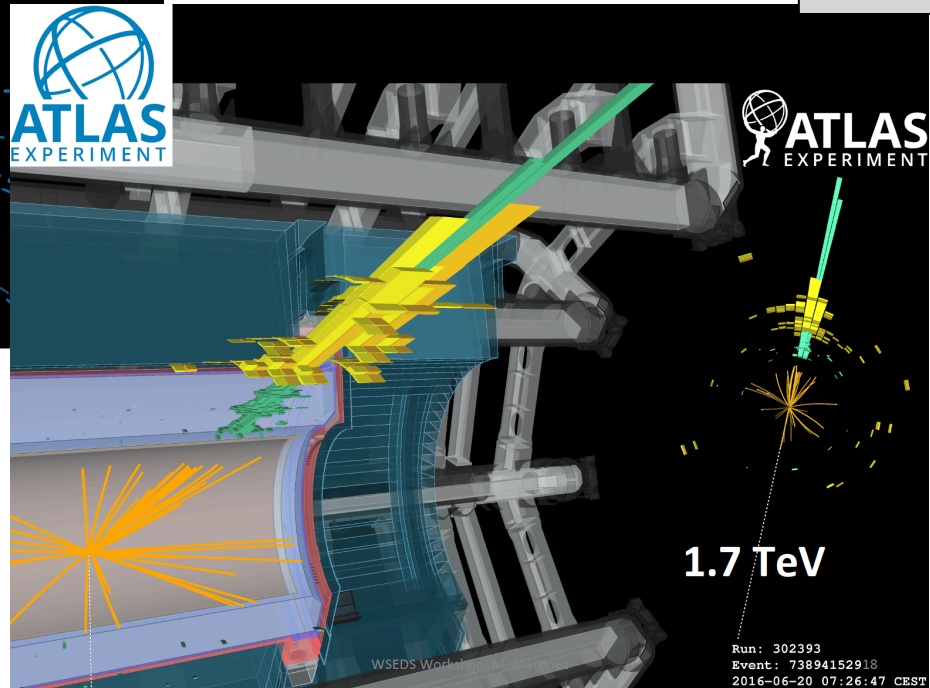
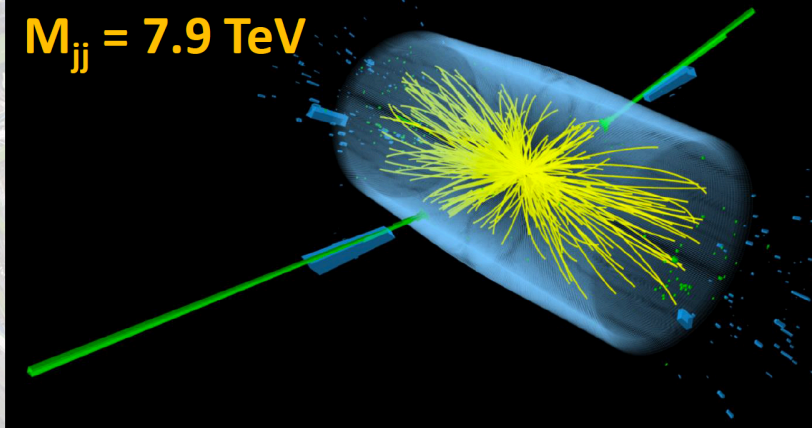
Dorigo

SEARCHES IN DIJET EVENTS



CMS Experiment at the LHC, CERN
Data recorded: 2016-May-11 21:40:47.974592 GMT
Run / Event / LS: 273158 / 238962455 / 150

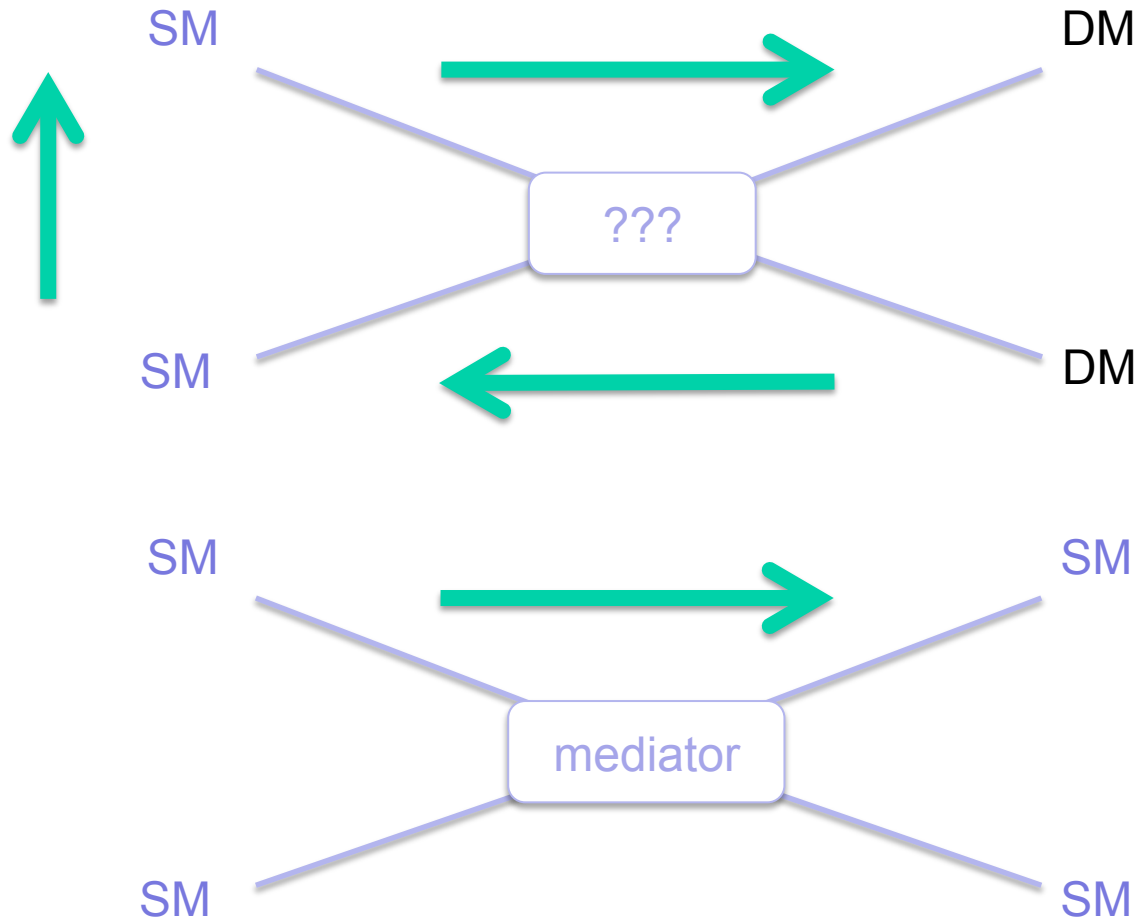
$M_{jj} = 7.9 \text{ TeV}$



Martinez

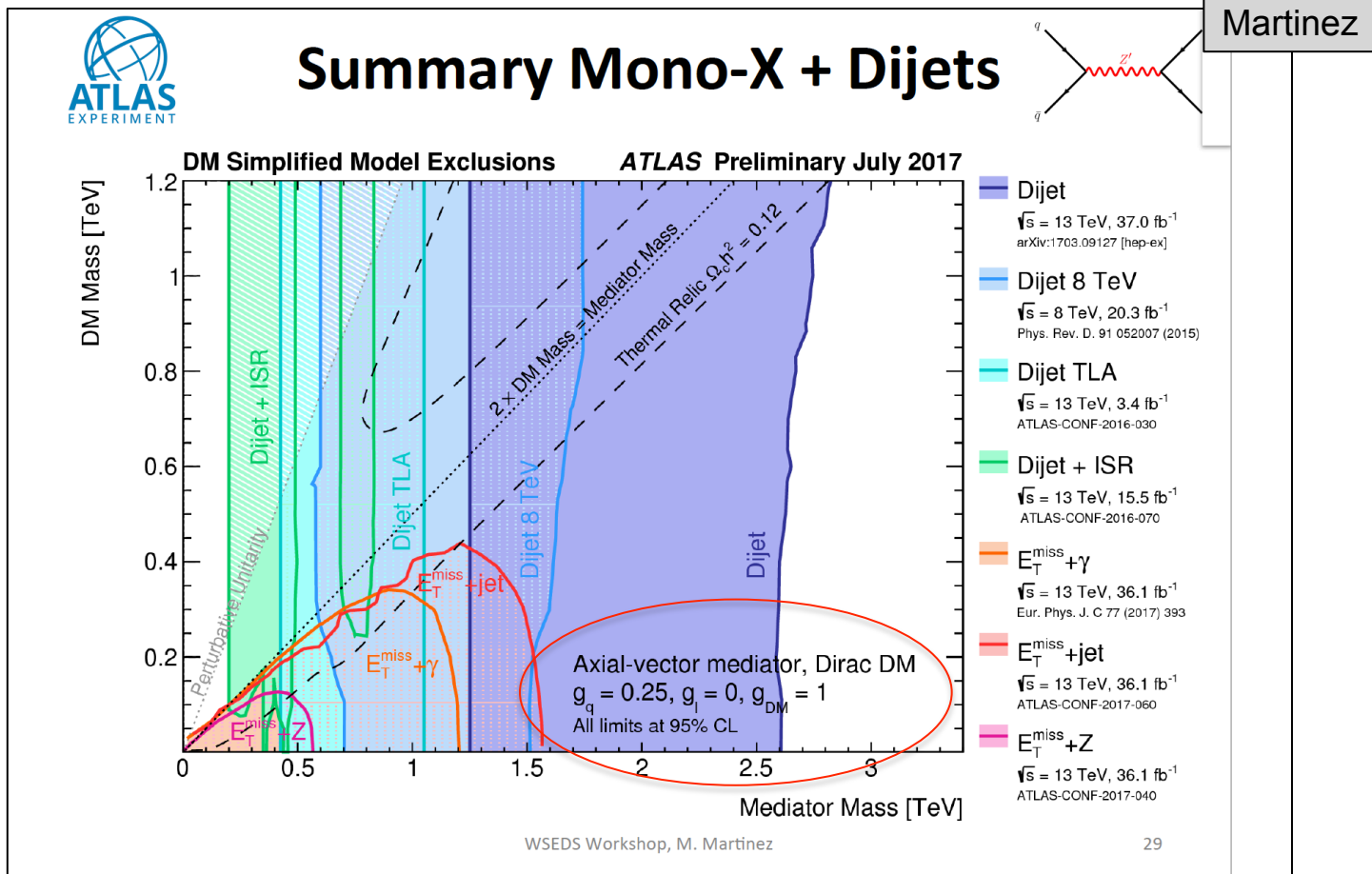


What's missing in the complementarity diagram



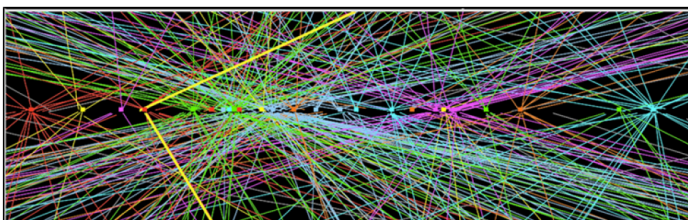
- Important point: for many models, the strongest constraint on thermal DM comes from searches for the mediator, i.e., di-jet searches.

DM Implications of LHC Searches



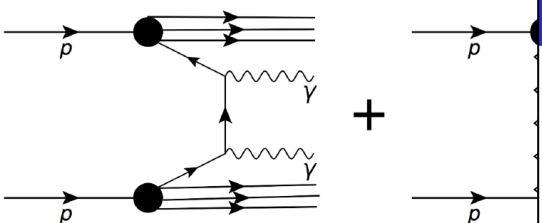
- Mono-jet search (red) looks for missing transverse energy from DM particle but is limited by high missing energy cut need to reduce background
- Di-jet search (blue) looks for DM mediator particle producing pairs of SM particles and can reach higher energies

Non-WIMP Accelerator Searches



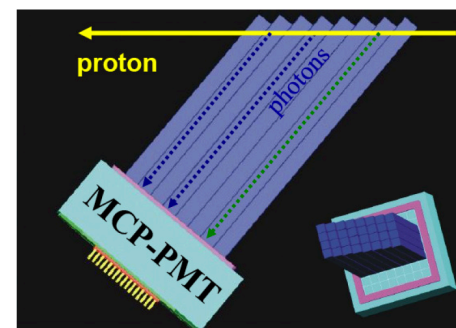
Williams

Royon



Timing detectors

- Measure the vertex position using proton time-of-flight: allows to determine if protons originate from main interaction vertex
- Requirements for timing detectors
 - 10 ps final precision (factor 40 rejection on pile up)
 - Efficiency close to 100% over the full detector coverage
 - High rate capability (bunch crossing every 25 ns)
 - Segmentation for multi-proton timing
 - level 1 trigger capability
- Utilisation of quartz, diamond, gas or Silicon detectors



Searching for DM and ED at the LHC with intact protons

25 / 32

Searching for anomalies in the proton scattering near the LHC beamline caused by new operators.

Technical challenge, reducing the beam backgrounds, requires amazing time resolution (~ 10 ps)



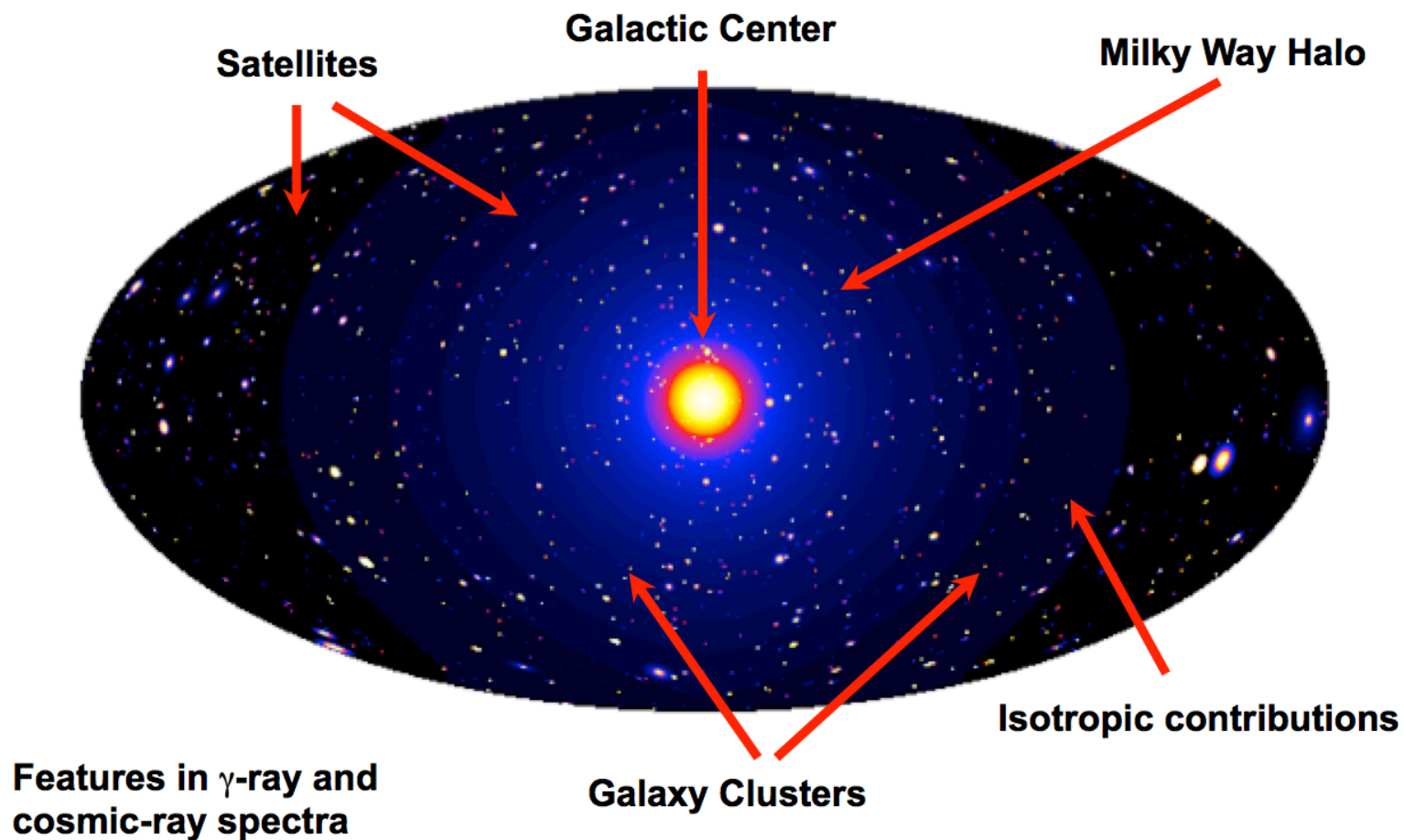
INDIRECT DETECTION

What signal would DM annihilation to γ -rays make?



14

Dark Matter as Seen From Earth

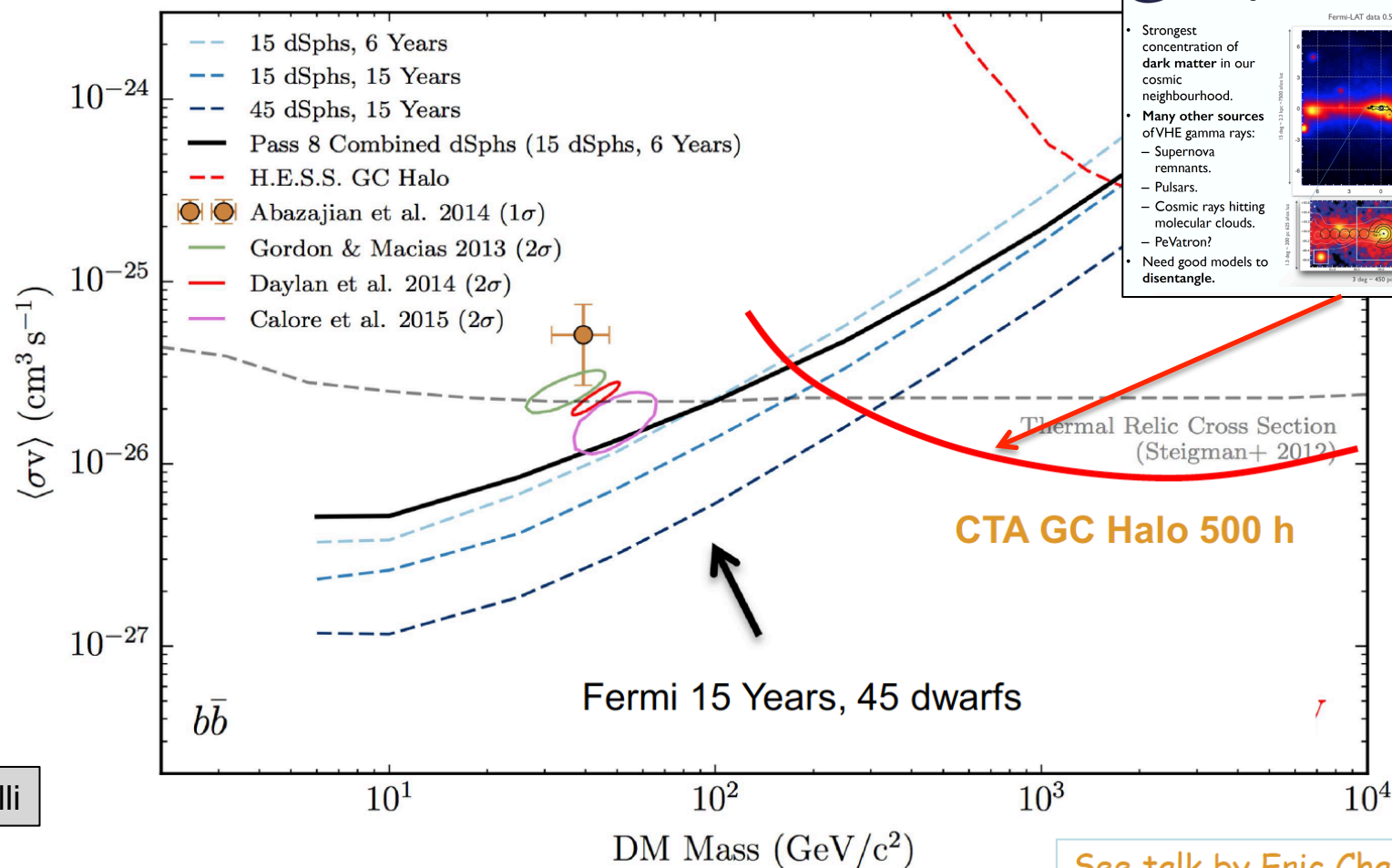


Dark Matter simulation: [Pieri+ \(2011\)](#)

Summary of Indirect Detection Searches

DM limit improvement estimate in 15 years (2008- 2023)

Gomez-Vargas



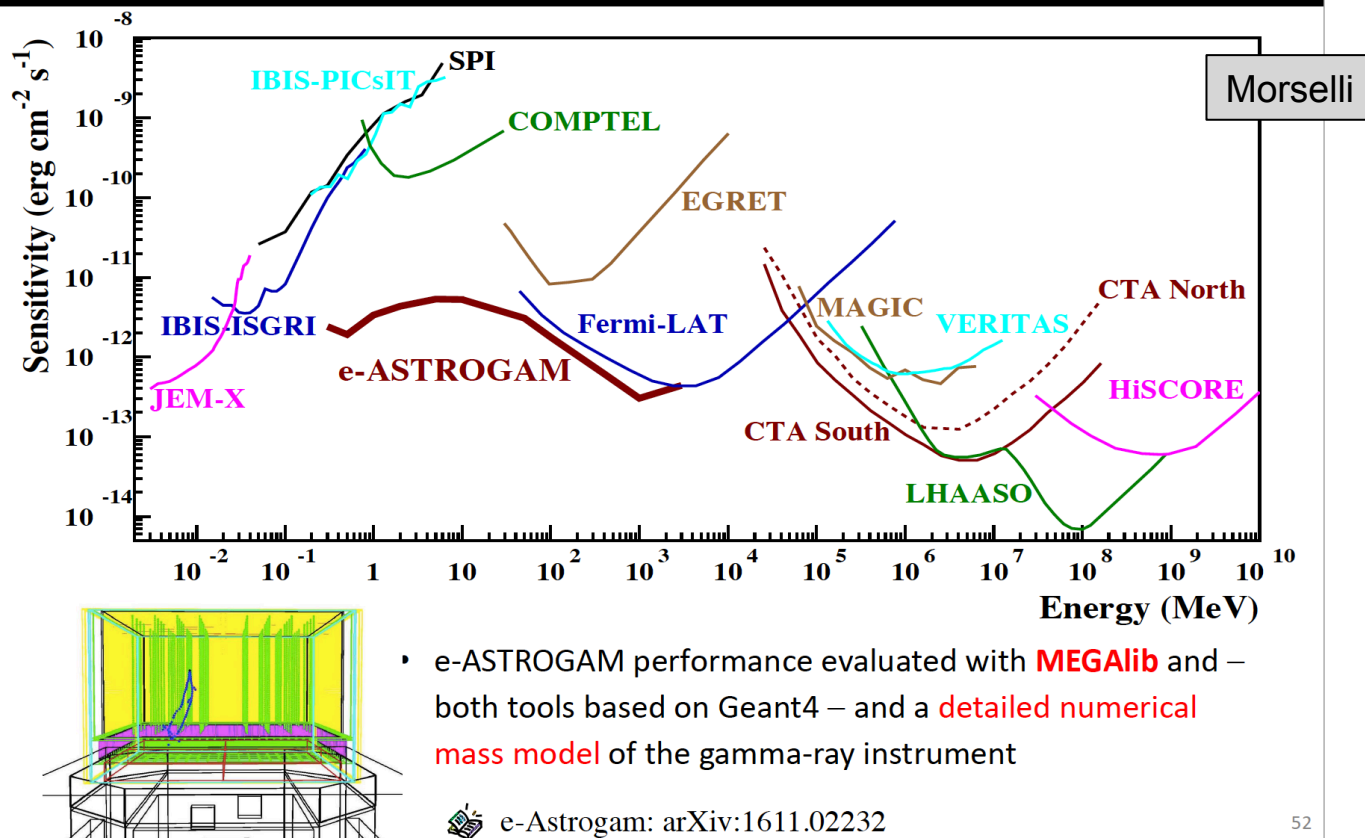
Morselli

See talk by Eric Charles

Together Fermi and CTA will probe most of the space of WIMP models with thermal relic annihilation cross section

The unexplored MeV energy band

e-ASTROGAM Performance assessment



52

Great science case for MeV mission, current designs are 100x more sensitive than COMPTEL.

Such missions would be sensitive to low-mass WIMPs

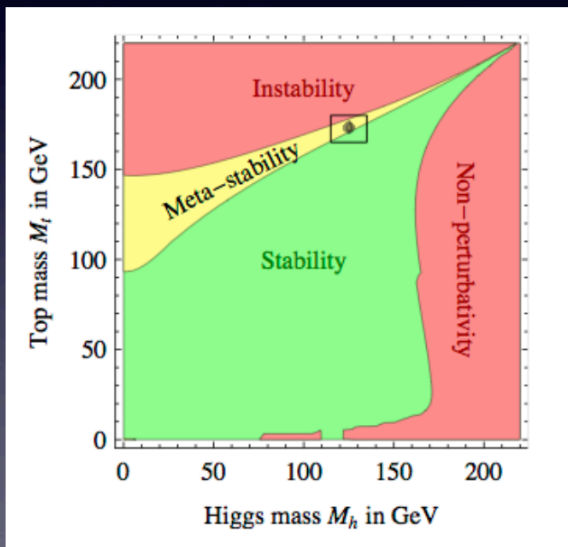


COSMOLOGY & ASTROPHYSICAL DARK MATTER

Inferred DM constraints

Moss

Stability regions*

 $O(\hbar^2)$ 

The potential depends on the Higgs and Top mass

$$V_{\text{eff}} = \frac{1}{4} \lambda_{\text{eff}}(\phi) \phi^4$$

where

$$\frac{d\lambda_{\text{eff}}}{d \ln \phi} = \beta_\lambda - 4\gamma \lambda_{\text{eff}}$$

*Degrassi et al arXiv:1205.6497

“There is observational evidence that the false vacuum has not decayed by seeded nucleation” -> no PBHs below 10^{15}g



Recent “excesses/anomalies”

Vincent

3.5 keV line
21 cm (EDGES)
AMS-02 antiprotons
PAMELA/AMS positron
Galactic centre GeV excess
Solar composition problem
White dwarf cooling anomaly
...

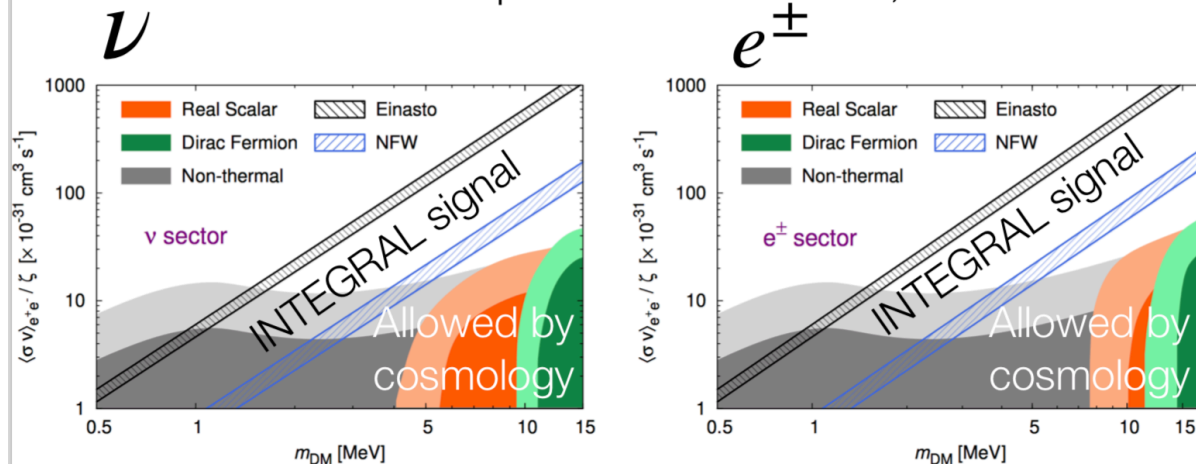


need strong
corroboration
because
astrophysics is
not a controlled
setting:
backgrounds
are difficult to
model

Complete constraints on a WIMP origin of 511 keV

Vincent

Thanks to Planck-provided **likelihoods**, can MCMC:



WIMP scenario seems disfavoured

Wilkinson... AV 2016

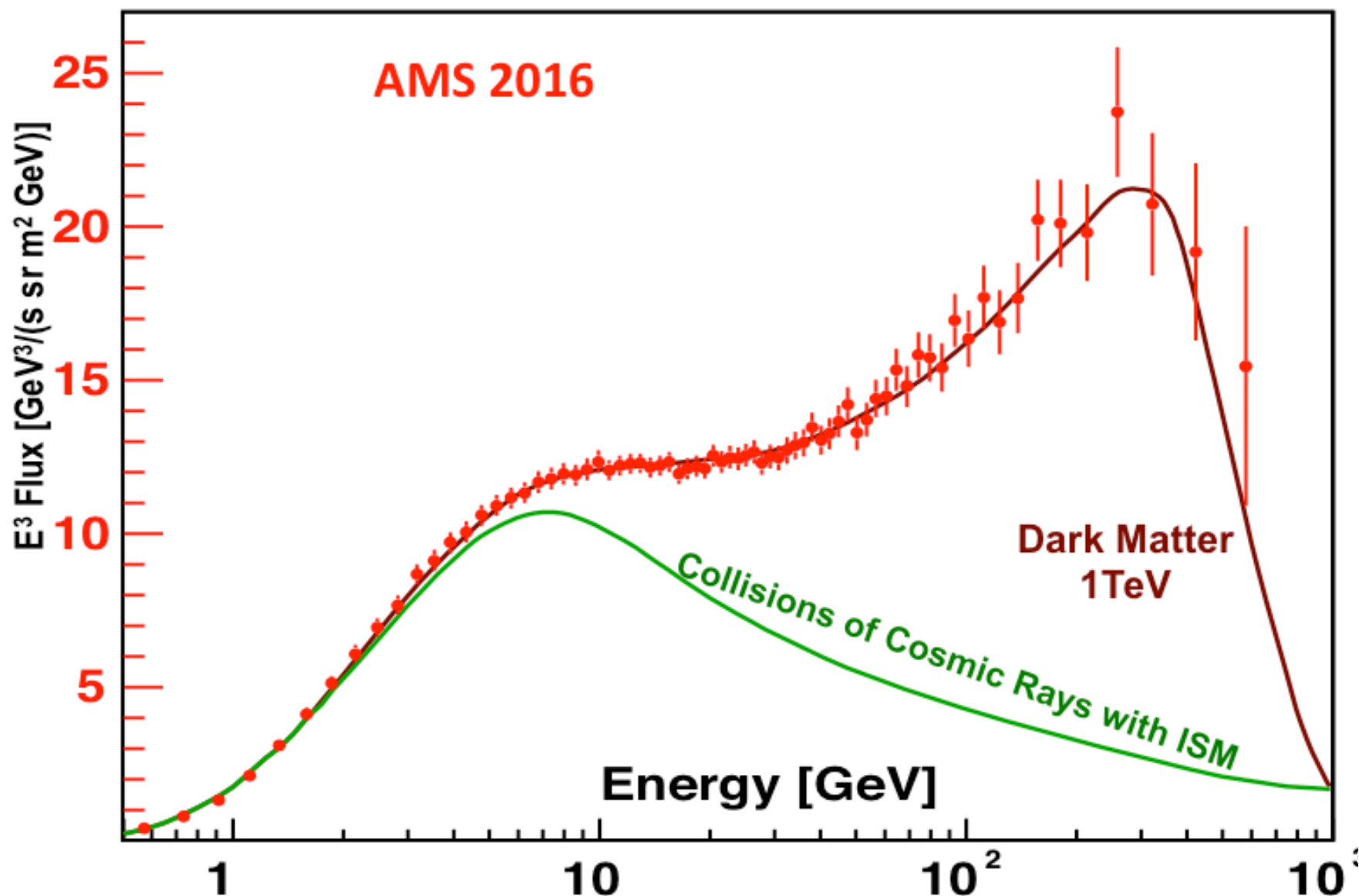
27

Key point here: this analysis is testing DM interpretation of Integral 511 keV data by comparing results to the non-observation of DM annihilation products ionizing the CMB.



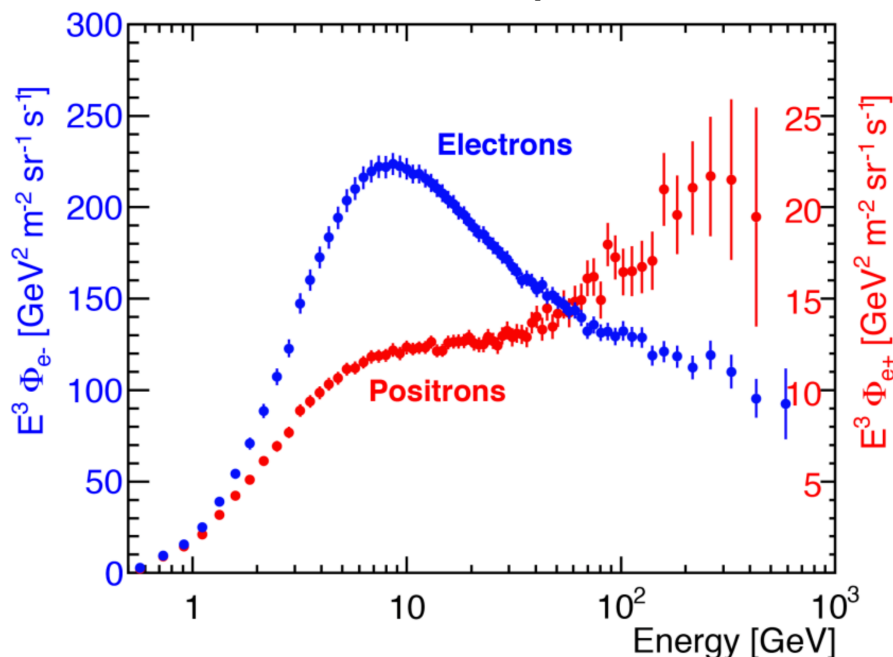
From questions and discussions: what about cosmic rays?

40

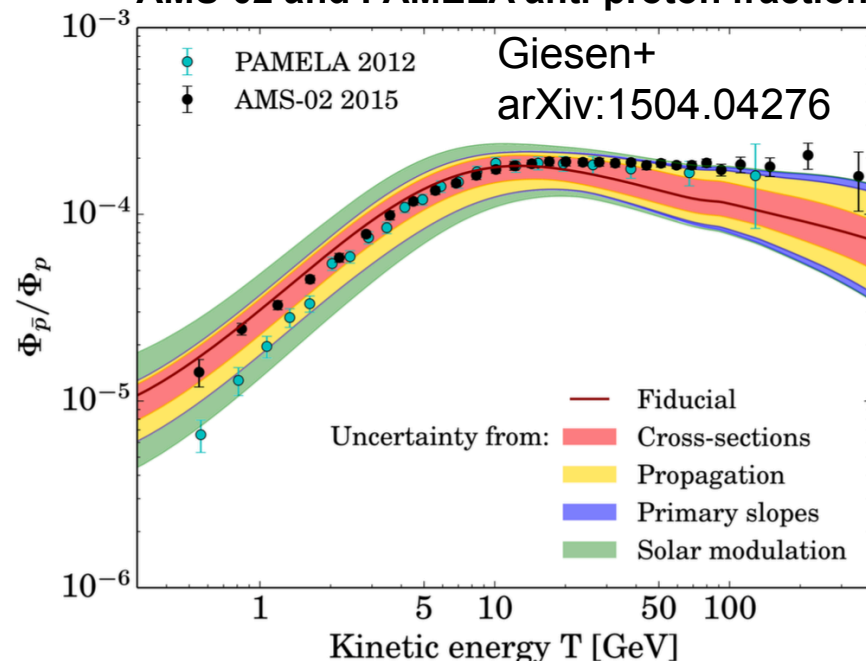


DM Limits from Cosmic-Ray Spectra

AMS-02 electron and positron fluxes

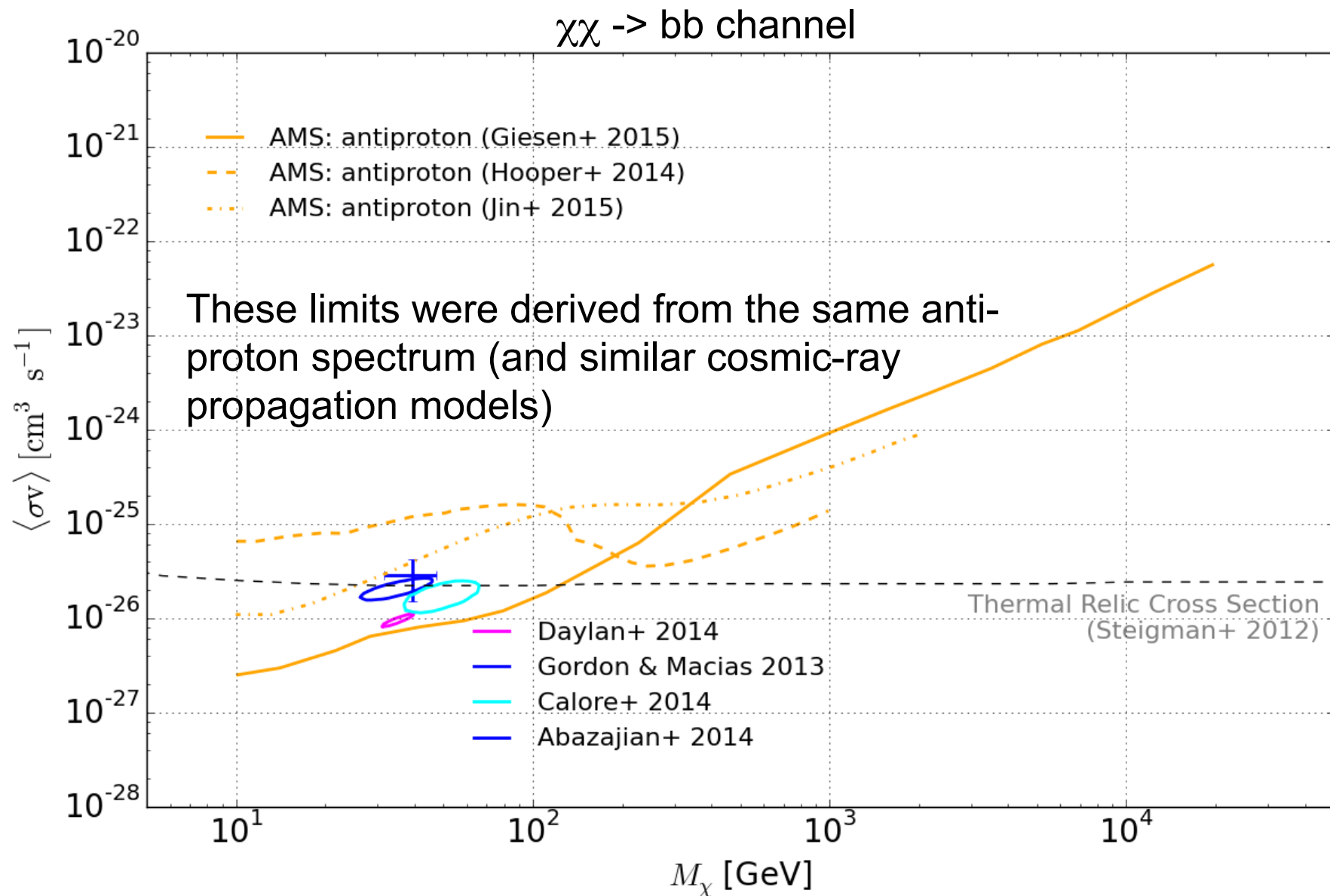


AMS-02 and PAMELA anti-proton fraction



- Extracting constraints on DM cross section from anti-particle fluxes requires detailed modeling of source populations, cosmic-ray propagation and other astrophysical effects (see sources of uncertainty on right figure).

Published Limits from Anti-Proton Spectra





The Good News

- No convincing (or even particularly compelling) DM signals in any searches: be they direct, indirect or accelerator-based
 - Some things that have been interpreted as signals are now strongly disfavored by other measurements (e.g., DAMA/LIBRA) or face strong competing hypotheses (e.g., positron fraction, Galactic center GeV excess)
- This is a great application of the scientific method: we are finding ways of testing (and falsifying) hypotheses & developing new hypotheses
- Dark matter is more interesting than a simple ~ 100 GeV thermal relic WIMP



The Even Better News

- Many impressive efforts are underway:
 - to understand what the astrophysical data are telling us about the nature of dark matter
 - to continue to test the dominant WIMP paradigm by building more sensitive experiments and better understanding backgrounds
 - to develop ways to test other types of DM candidates
- This is a great application of the scientific method: we are finding ways of testing (and falsifying) hypotheses & developing new hypotheses
- We know that dark matter exists, perhaps we might be very lucky to discover that its particle nature is more interesting than, say, a ~ 100 GeV thermal relic WIMP from one of the simpler SUSY models



**QUESTION: WHAT IF NATURE IS UNKIND AND DARK MATTER
INTERACTIONS ARE NOT EASILY DETECTABLE?**

OR

**WHAT ELSE CAN WE LEARN ABOUT DM FROM
ASTROPHYSICS?**

Understanding the Astrophysical Nature of DM

<https://lsstdarkmatter.github.io/>

cold dark matter

warm dark matter

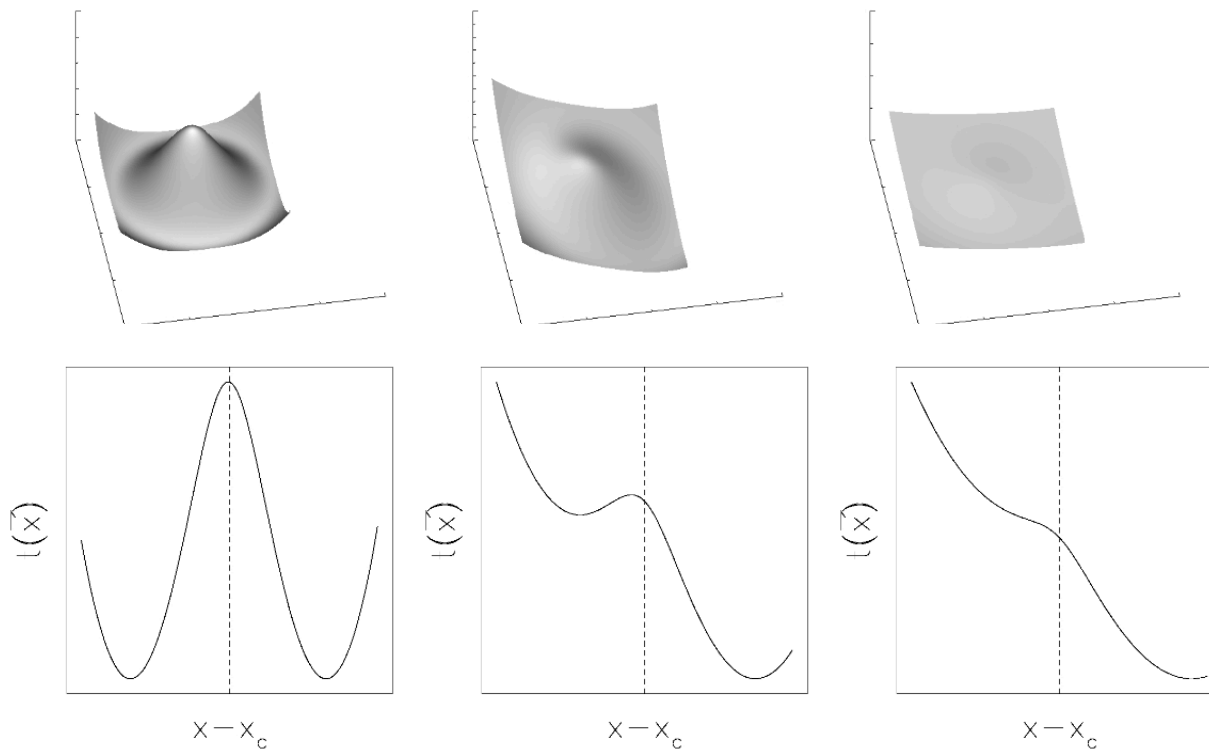
How can we distinguish between these?

Lovell+ (2012)



- Wide-area surveys (DES, Pan-STARRS, Gaia, LSST) identify and characterize DM-dominated structures
- Modern numerical simulations improve our understanding of the dependence on cosmology, DM particle properties, “baryonic” effects in structure formation

Aside: Strong Lensing



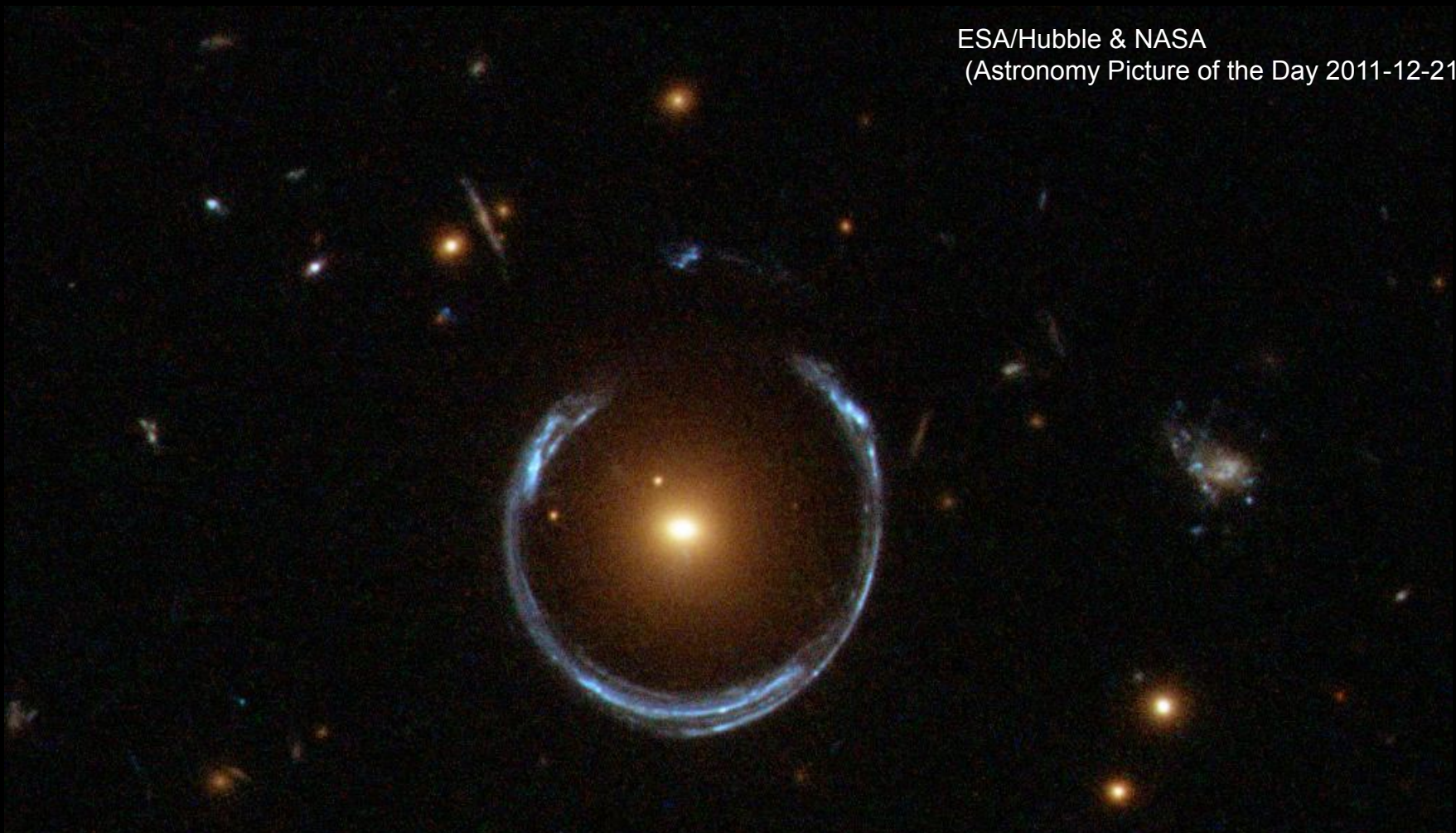
Einstein Ring

Einstein Cross

Weak Lensing

Light will appear for lines of sight where the gradient of the travel time is small: This includes minima, maxima and saddle points.

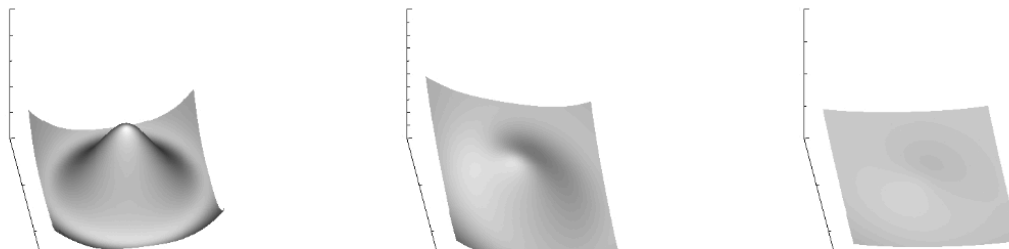
Aside: Gravitational Lensing



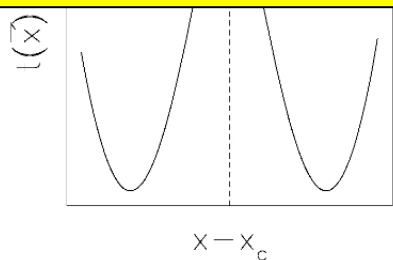
ESA/Hubble & NASA
(Astronomy Picture of the Day 2011-12-21)

Gravitational time dilation means that light from lensed galaxy (behind) reaches us more quickly by travelling around the lensing galaxy (in front).

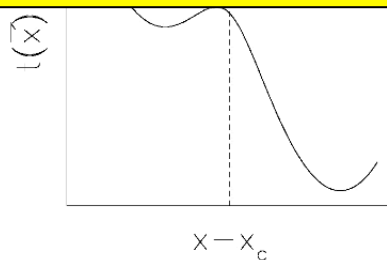
Aside: Strong Lensing



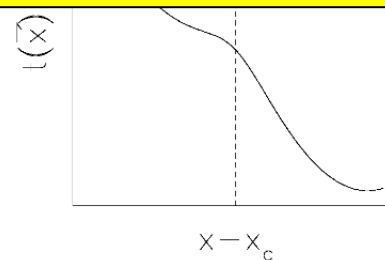
Key point for us: a strong lens creates a number of directions where the light travel time surface is flat: our sensitivity to lensing from sub-halos along these lines of sight is vastly improved



Einstein Ring



Einstein Cross



Weak Lensing

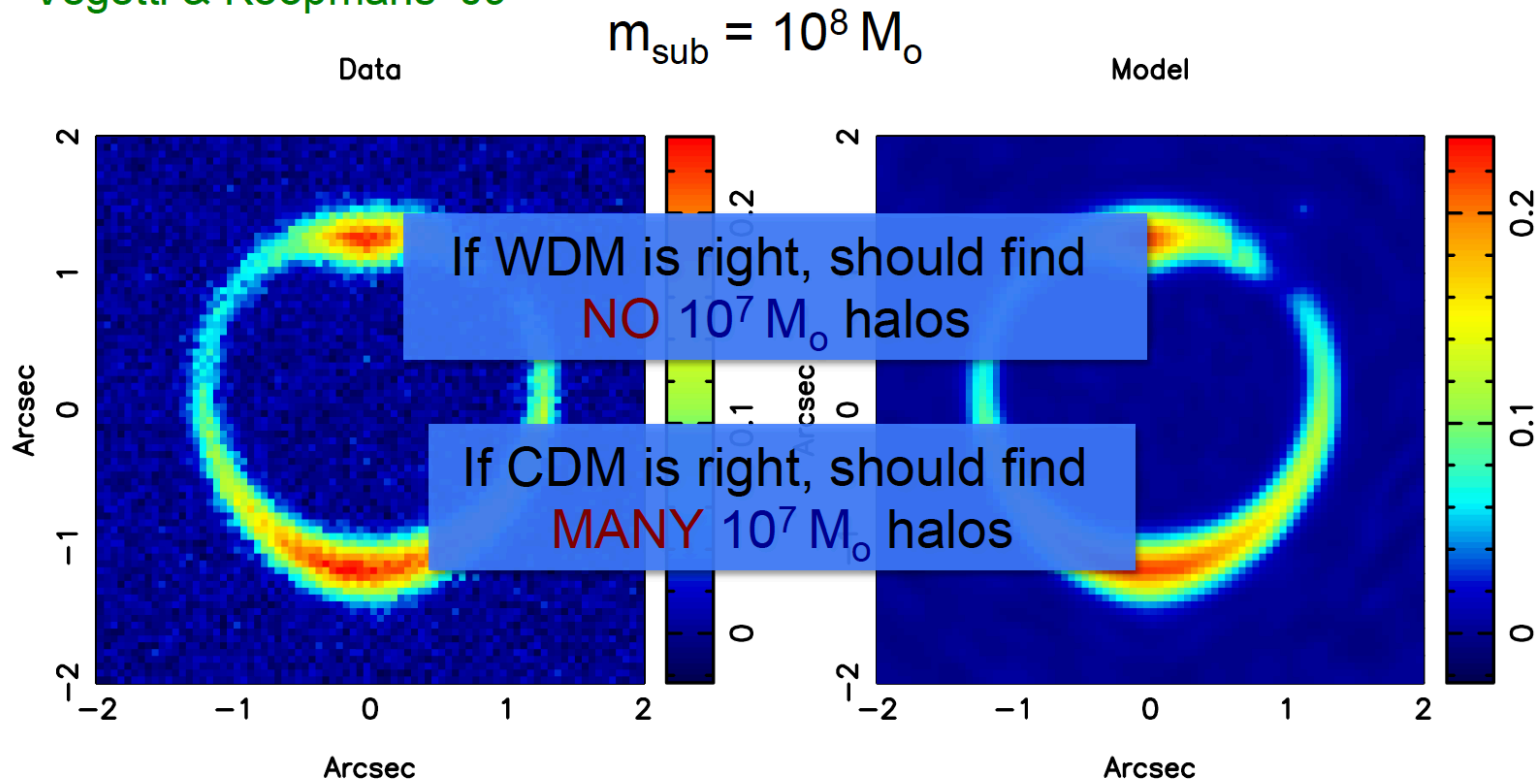
Light will appear for lines of sight where the gradient of the travel time is small: This includes minima, maxima and saddle points.

Measuring Strong Lensing Substructure Will Resolve CDM v. WDM



Detecting substructures with strong lensing

Vegetti & Koopmans '09



Can detect subhalos as small as $10^7 M_{\odot}$



Other upcoming inputs from astrophysics

- Gaia is measuring proper motion and peculiar velocities of the stars in our galaxy and tracing out the Galactic gravitational potential
- Large scale surveys (DES, Pan-STARRS...) are finding new dwarfs and comparing properties to numerical simulations
- Gravity wave experiments are teaching us about the BH mass function and merger rate
- Neutrino astronomy is pushing observable horizon for high-energy events
- Cluster mergers / kinematics are teaching us about dark matter self-interaction rate
- Cosmology is pinning down the process of structure formation



Thank You

